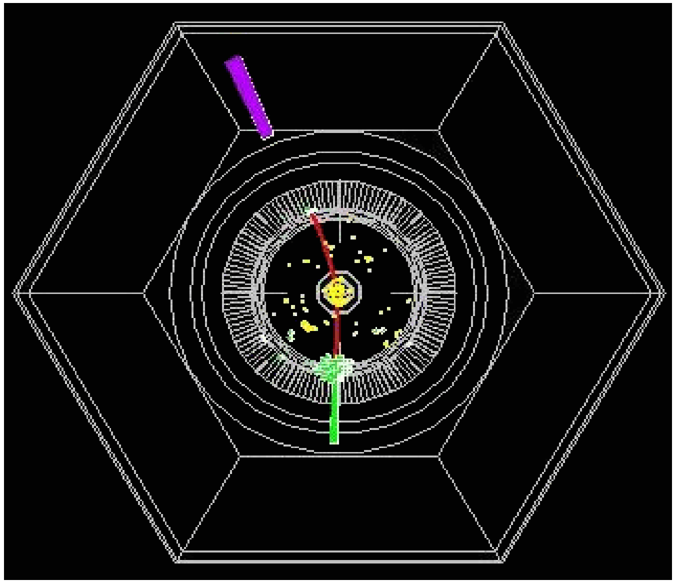
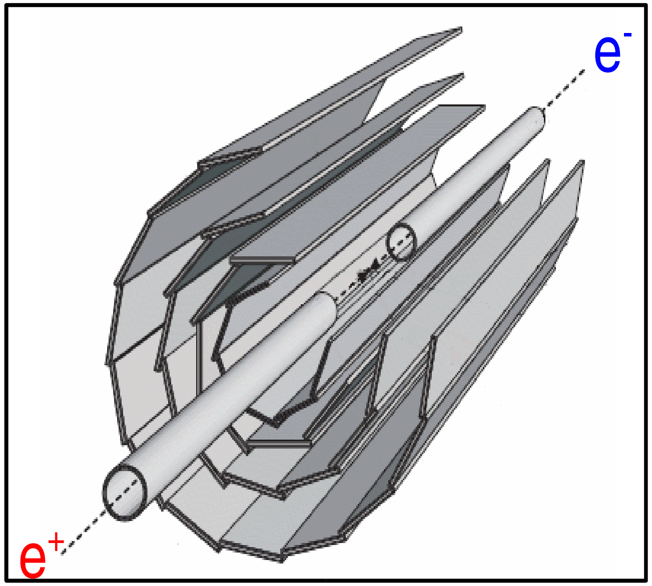
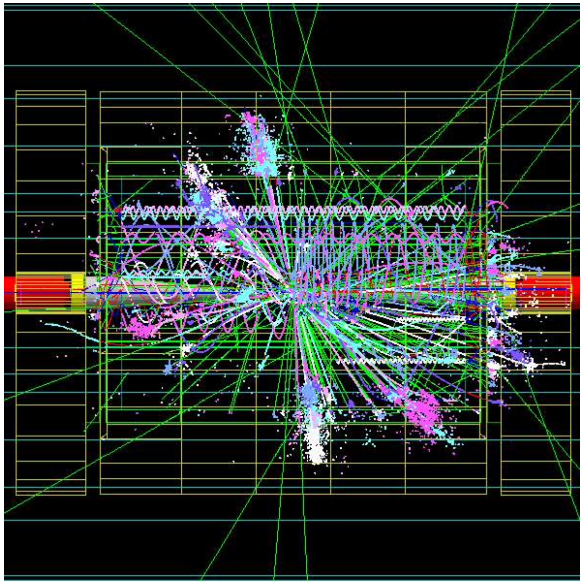
Strategies for New Physics Searches at Lepton Colliders



Search for Charged Lepton Flavor Violation at BaBar



Silicon Detector R&D for a future Lepton Collider Vertex Tracker



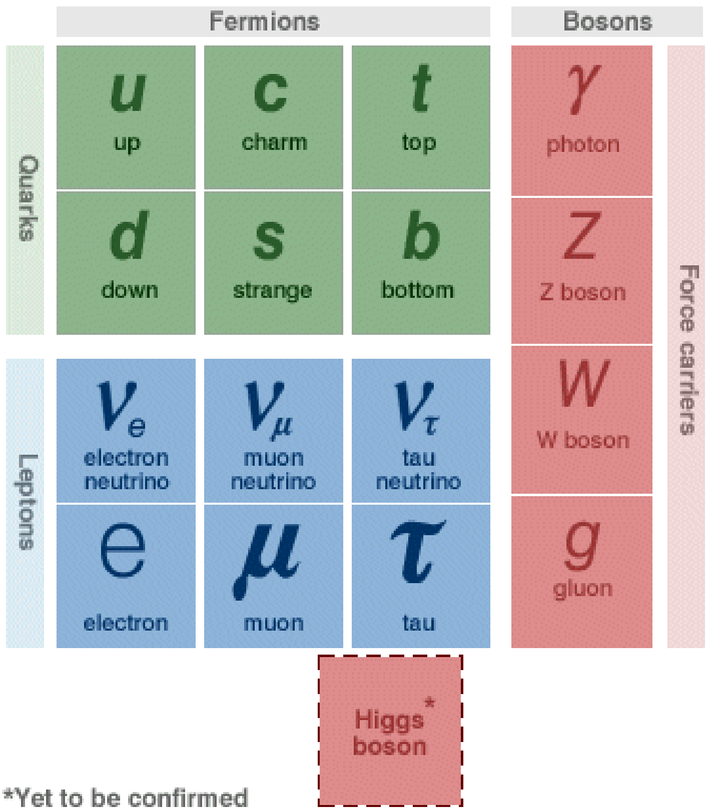
DM-Motivated SUSY at a Future Lepton Collider

Table of Contents

- Introduction
- Probing TeV-scale physics with low energy data
  - Search for lepton-flavor violating decays at BaBar
- Detector R&D for a future TeV-scale lepton collider
  - R&D of thin sensors and construction of a vertex tracker prototype
- Searching for new physics at a TeV-scale lepton collider
  - Simulation studies of a dark-matter motivated Supersymmetry scenario

The Current State of Particle Physics

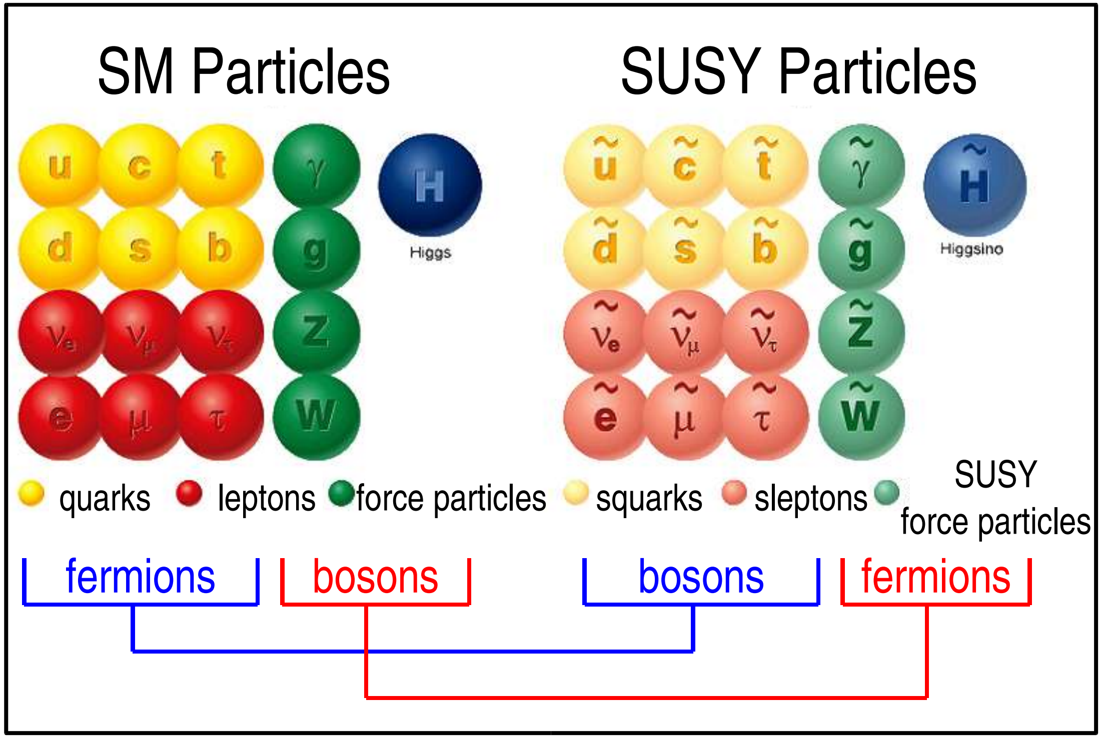
The Standard Model of Particle Physics: quantum field theory describing the fundamental particles & forces



- **SM** extremely successful up to highest energies ~10^2 GeV probed by experiment of, but it cannot be the final theory:
  - Why is $M_{higgs} << M_{Planck}$? (hierarchy problem)
  - Gauge coupling unification
  - CP violation?
  - Neutrino Masses
  - **Dark matter** and dark energy
- Expect new physics to manifest at the TeV scale
  $\rightarrow$ **B**eyond **S**tandard **M**odel physics
- **SU**per**SY**mmetry: solves many problems intrinsic to **SM**, may explain origin of dark matter

SUperSYmmetry and Dark Matter

- SUSY: symmetry relates fermions ↔ bosons
- Introduces 'Superpartners' at **E**lectro**W**eak **S**ymmetry **B**reaking scale $O(10^2)$ GeV
- SUSY may explain origin of DM
  - Define R-parity $R=(-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases}$
  - R-parity conservation→ **L**ightest **S**USY **P**article is stable
  - χ_1^0 neutralino LSP: neutral, stable →DM candidate particle with $M_\chi=O(10^2)$ GeV

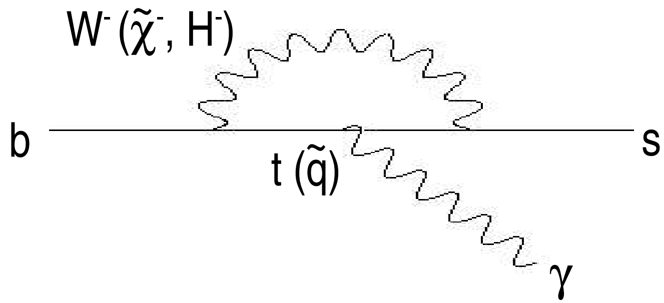


- WMAP measurements of CMB: **DM relic density $\Omega_{DM}=\rho_{DM}/\rho_{crit} = 0.233 \pm 0.013$**
- WIMP with mass $O(10^2)$ GeV experimentally favored→ DM composed of SUSY particles? To be probed at LHC, future TeV-scale lepton collider

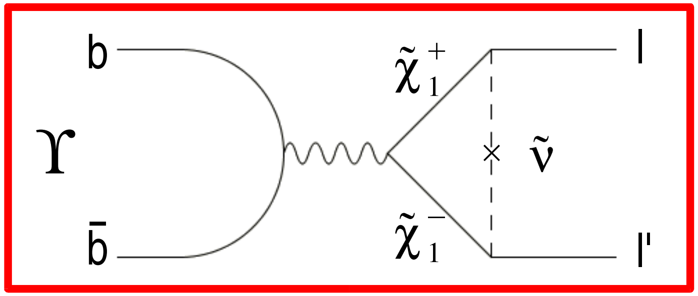
(B=baryon #, L=lepton #, s=spin)

Two Strategies for NP Searches

low energy: precision effects

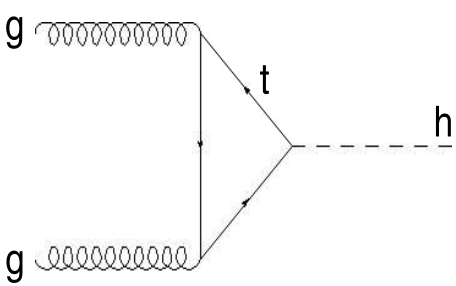


Flavor-Changing Neutral Current Loop Diagram

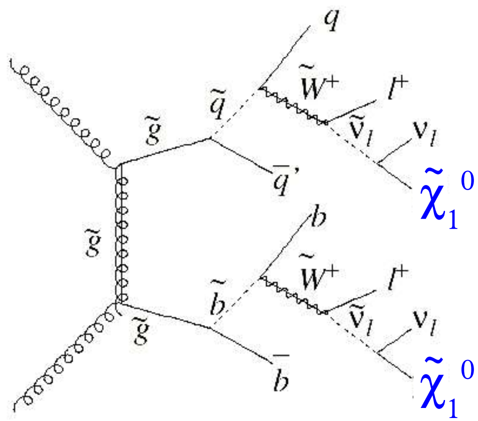


Lepton Flavor Violating SUSY loop

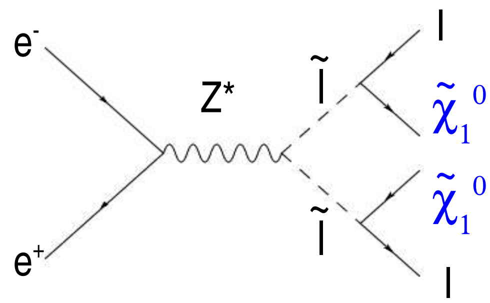
high energy: direct production



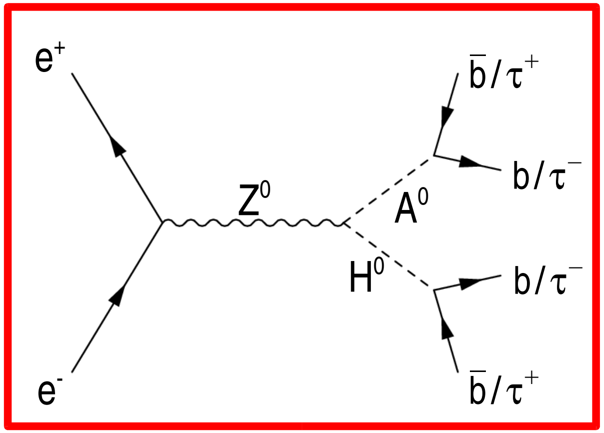
gg-Fusion Higgs Production (LHC)



$\tilde{g}\tilde{g}$ Production with Cascade(LHC)



Slepton Pair Production (LC)



H^0A^0 production (LC)

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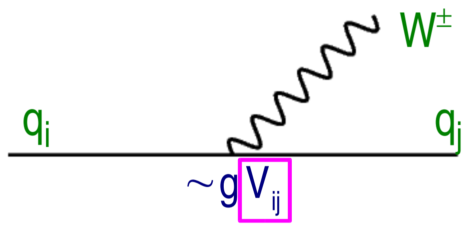
Lepton Flavor Violation (LFV)

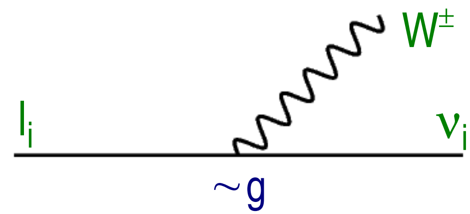
Minimal SM Processes

Flavor-Changing Quark Transition



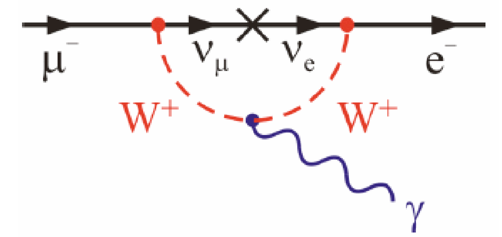
unitary matrix allows quark flavor mixing

Flavor-Conserving Lepton Transition



no mixing matrix→ conservation of lepton flavor

SM with $m_\nu \neq 0$ Processes

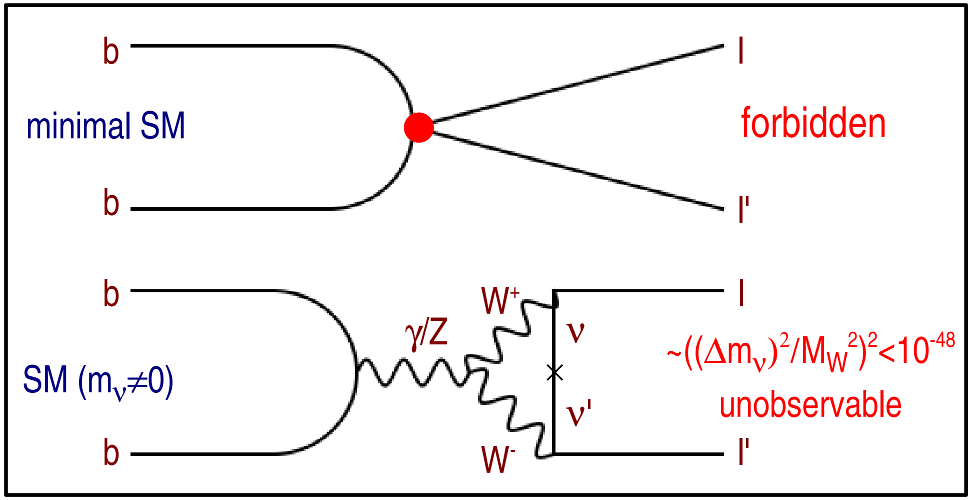


$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 \sim 10^{-52}$$

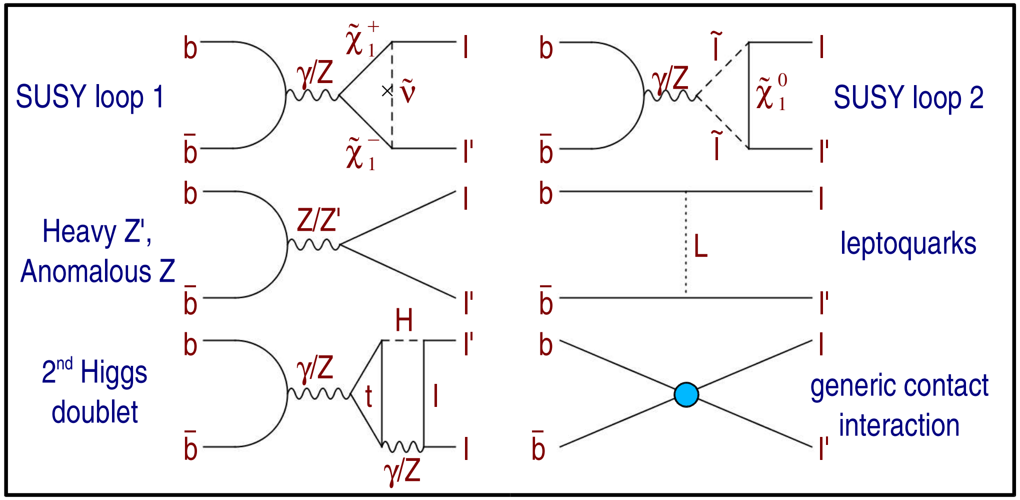
- In minimal SM (m_ν=0), quark flavor is violated but lepton flavor is conserved
- $m_\nu \neq 0 \to$ neutrinos oscillate between flavors$\to$ **neutral** lepton flavor violation
- Even with neutrino masses added to SM, **C**harged **L**epton **F**lavor **V**iolating processes (ie. $\mu \to e\gamma$) are suppressed by $((\Delta m_\nu)^2/M_W^2)^2 \to$ unobservable
- Observation of **CLFV**$\to$ unambiguous signal of new physics

CLFV in ϒ Decays at BaBar

SM Diagrams

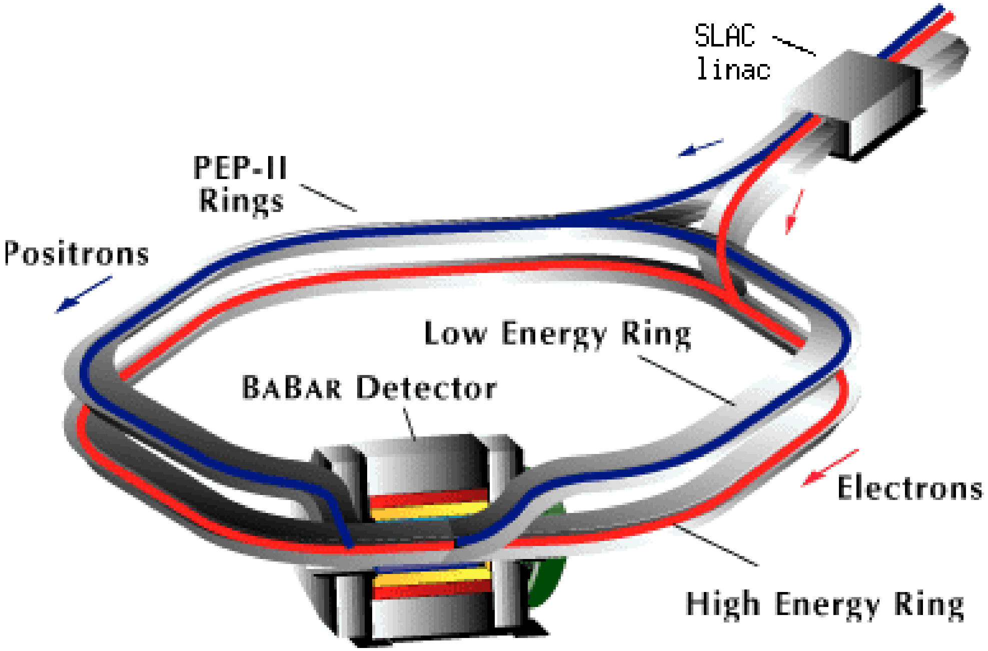


beyond SM Diagrams

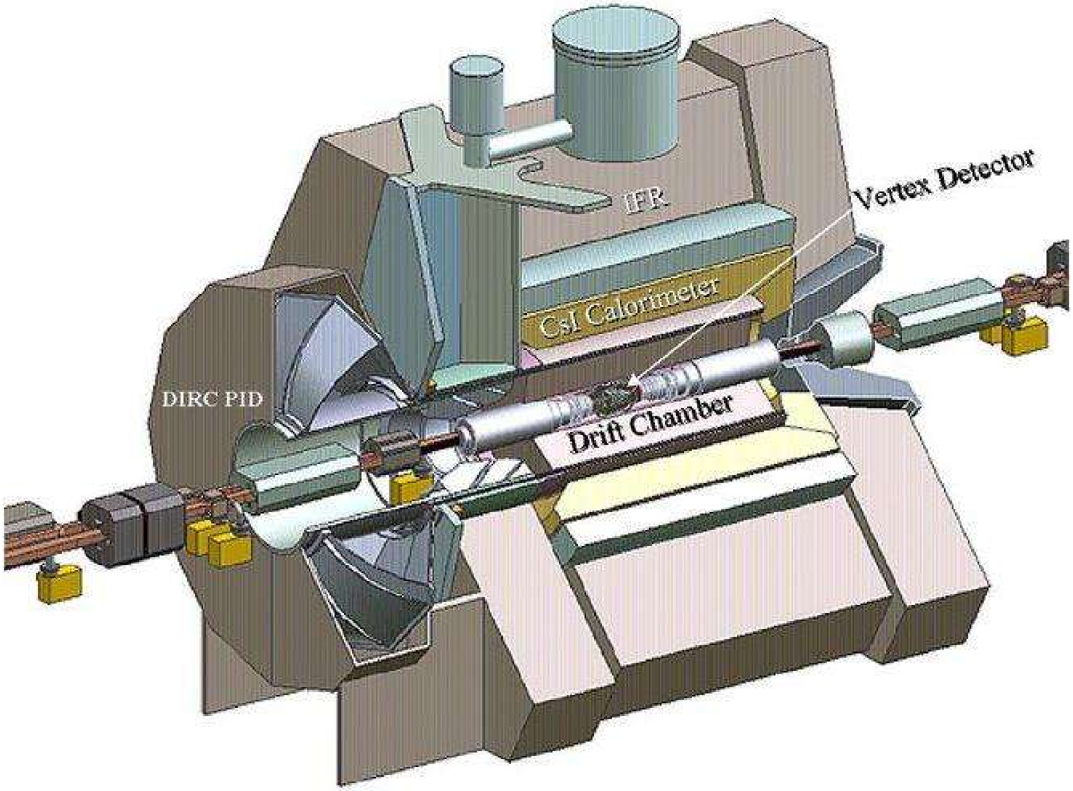


- CLFV decays ϒ unobservable in SM, but many BSM mechanisms allowed
- BF(ϒ→CLFV) >> BF(μ/τ→CLFV) possible (Nussinov et al. hep-ph/0004153)
- Process probes TeV-scale physics at $E_{CM} \approx 10$ GeV
- **Strong motivation for CLFV search in ϒ decays at BaBar**
- Current UL from CLEO: BF(ϒ(3S)→μτ)<2.03×10^{-5} (CLEO PRL 101.201601)

The PEPII Collider and BaBar Detector

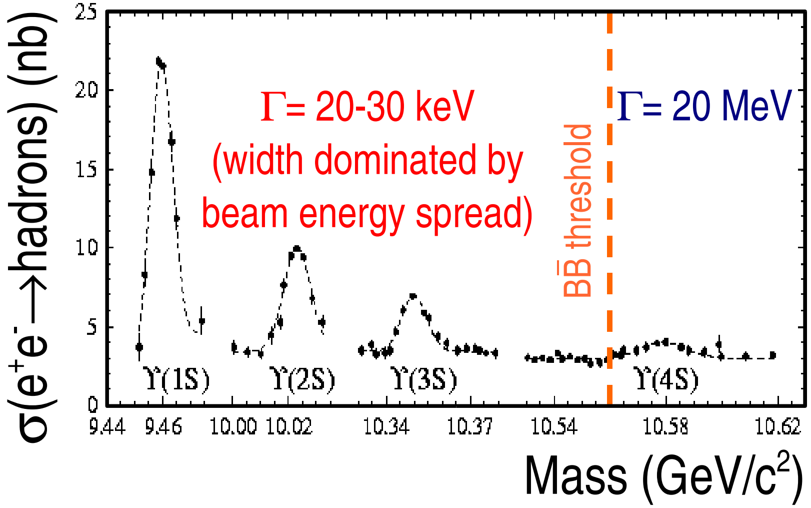


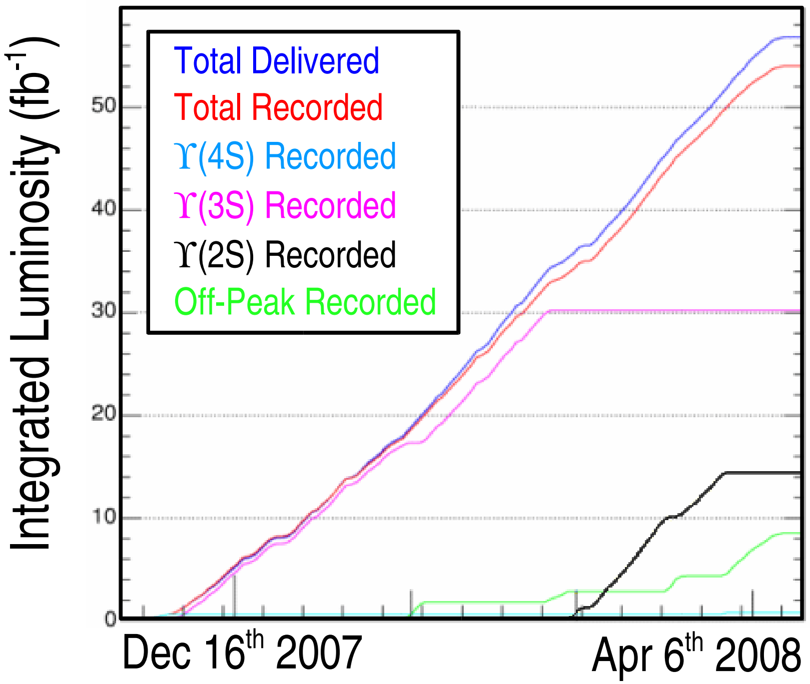
Asymmetric energy e^+e^- Collider



Υ(3S) Motivation

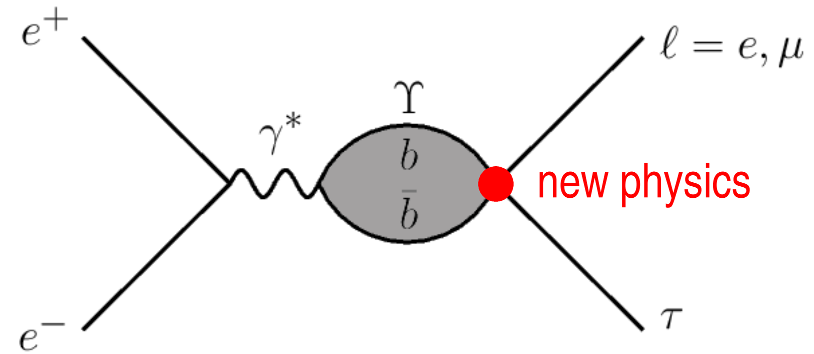
- Most BaBar data collected at $E_{CM}=M_{\Upsilon(4S)}>2M_B$ to search for CP violation in B meson decays
- At $E_{CM} = M_{\Upsilon(nS)}$ (n=1,2,3) branching fractions of rare Υ decays are increased roughly by $\Gamma_{\Upsilon(4S)} / \Gamma_{\Upsilon(nS)} \approx 10^3 \rightarrow$ dramatic increase in sensitivity to rare processes
- At end of PEP-II operations, collected **122×10^6 Υ(3S) decays**, 99×10^6 Υ(2S) decays to search for exotic decays





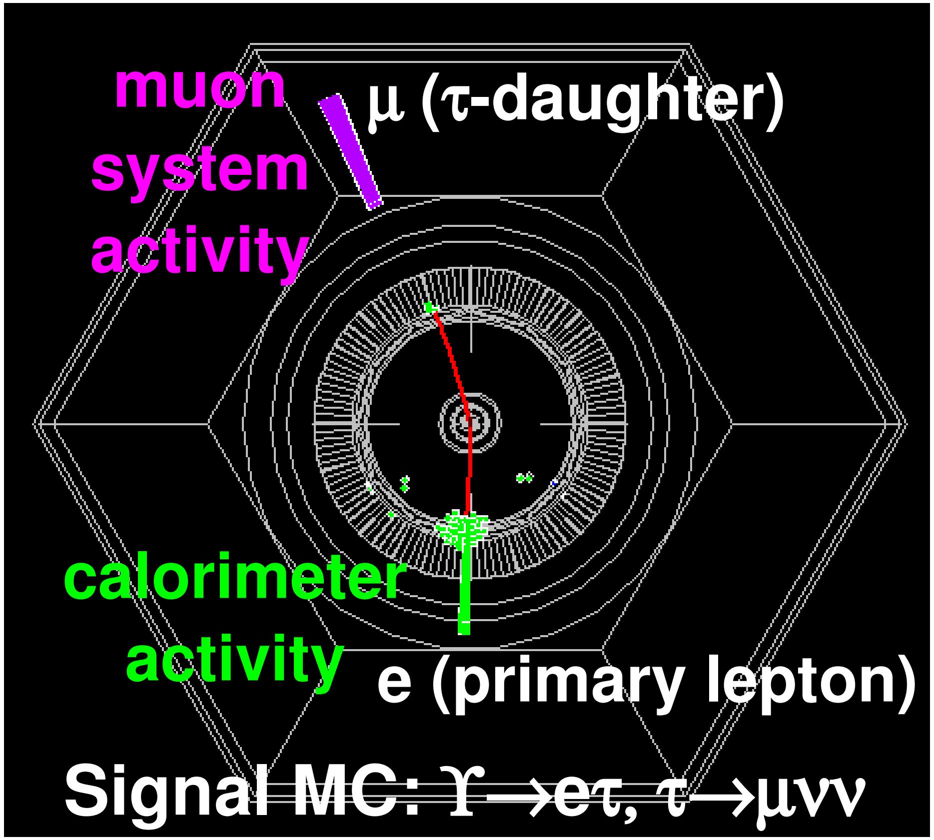
Signal Signatures and Channels

- Signal: $e^+e^- \to \Upsilon(3S) \to e\tau/\mu\tau$ production →



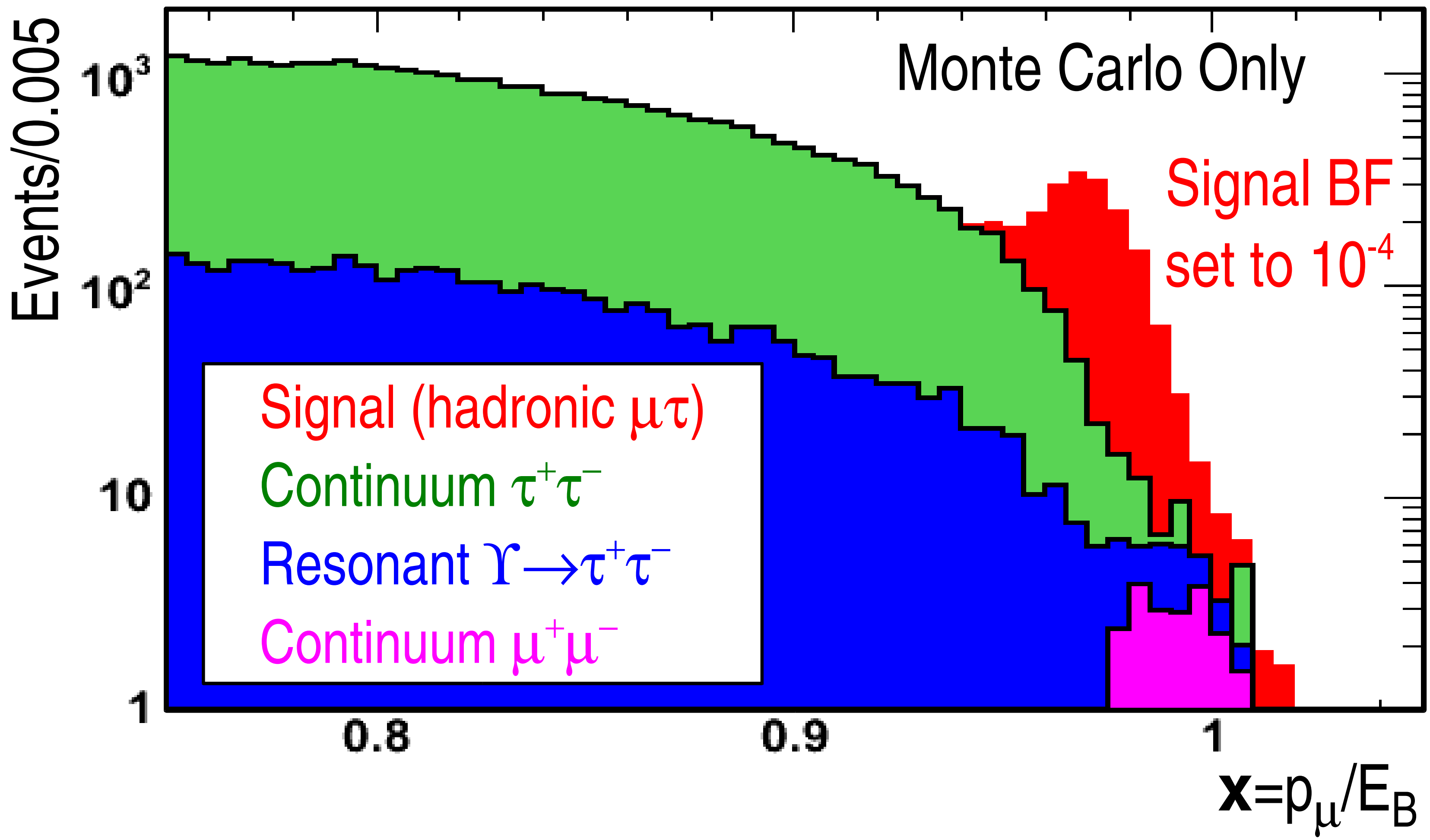
- Signature:
  - Primary lepton (e or μ) with close to full beam energy + τ decay in other hemisphere
  - τ required to decay to single charged particle (e,μ, $\pi^\pm$) + possible additional π^0's
  - Define 4 signal channels:

Process	τ Decay	Channel
$\Upsilon(3S) \to e\tau$	$\tau \to \mu\nu\nu$	leptonic eτ
$\Upsilon(3S) \to e\tau$	$\tau \to \pi^\pm\pi^0\nu/\pi^\pm\pi^0\pi^0\nu$	hadronic eτ
$\Upsilon(3S) \to \mu\tau$	$\tau \to e\nu\nu$	leptonic μτ
$\Upsilon(3S) \to \mu\tau$	$\tau \to \pi^\pm\pi^0\nu/\pi^\pm\pi^0\pi^0\nu$	hadronic μτ



Signal vs. Backgrounds

Discriminant variable **x** = primary lepton CM momentum / beam energy

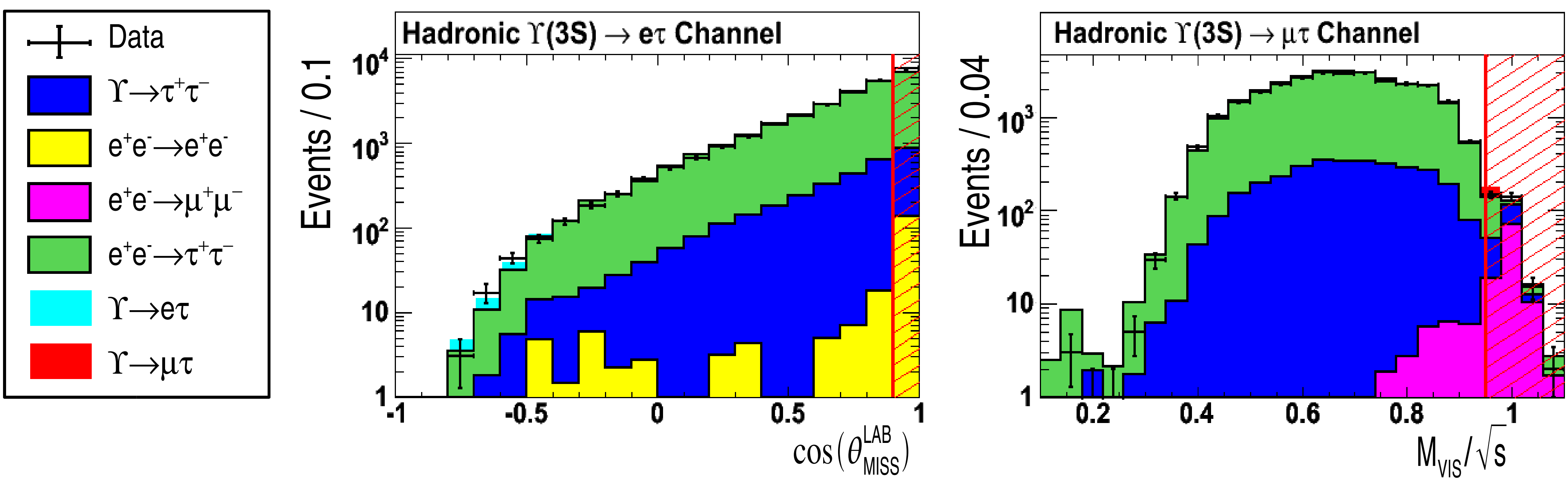


Perform maximum likelihood fit to **x** distribution for 4 signal channels

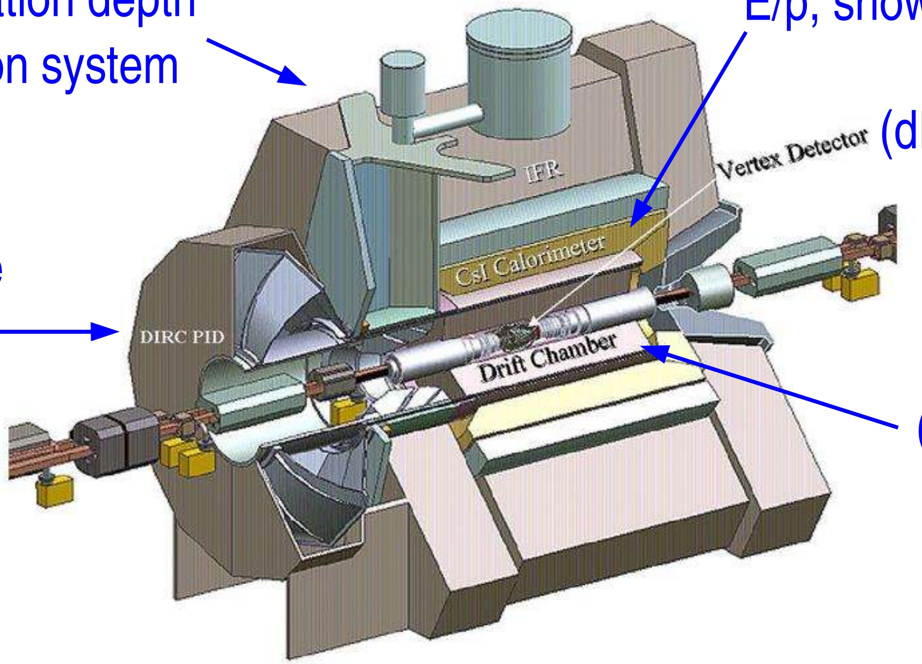
Event Pre-selection (All Signal Channels)

- 2 oppositely-charged tracks, one in each hemisphere
- Must pass requirements designed to select $e^+e^- \to \tau^+\tau^-$ events
- $\cos(\theta_{MISS}^{LAB}) < 0.9 \ \ \& \ \ \cos(\theta_{MISS}^{CM}) > -0.9 \ \ \& \ \ \frac{(\vec{p}_1 + \vec{p}_2)_\perp}{(\sqrt{s} - |\vec{p}_1| - |\vec{p}_2|)} > 0.2 \ \ \& \ \ \frac{M_{VIS}}{\sqrt{s}} < 0.95$

θ_{MISS} polar angle of missing momentum vector
p_i track CM momentum
M_{VIS} total visible mass in event
$\sqrt{s}$ CM collision energy



Particle Identification at BaBar



- Particle Identification: multivariate analysis of **information** from all detector subsystems
  - **electron**: e selector + μ veto + within calorimeter acceptance
  - **muon**: μ selector + e veto
  - **charged pion**: $\pi^{\pm}$ selector + e veto + μ veto
  - **neutral pion**: γ pair with 110 MeV/c^2<$M_{\gamma\gamma}$<160 MeV/c^2

Event Selection

classify events into 1 of 4 signal channels

further suppression of reducible backgrounds

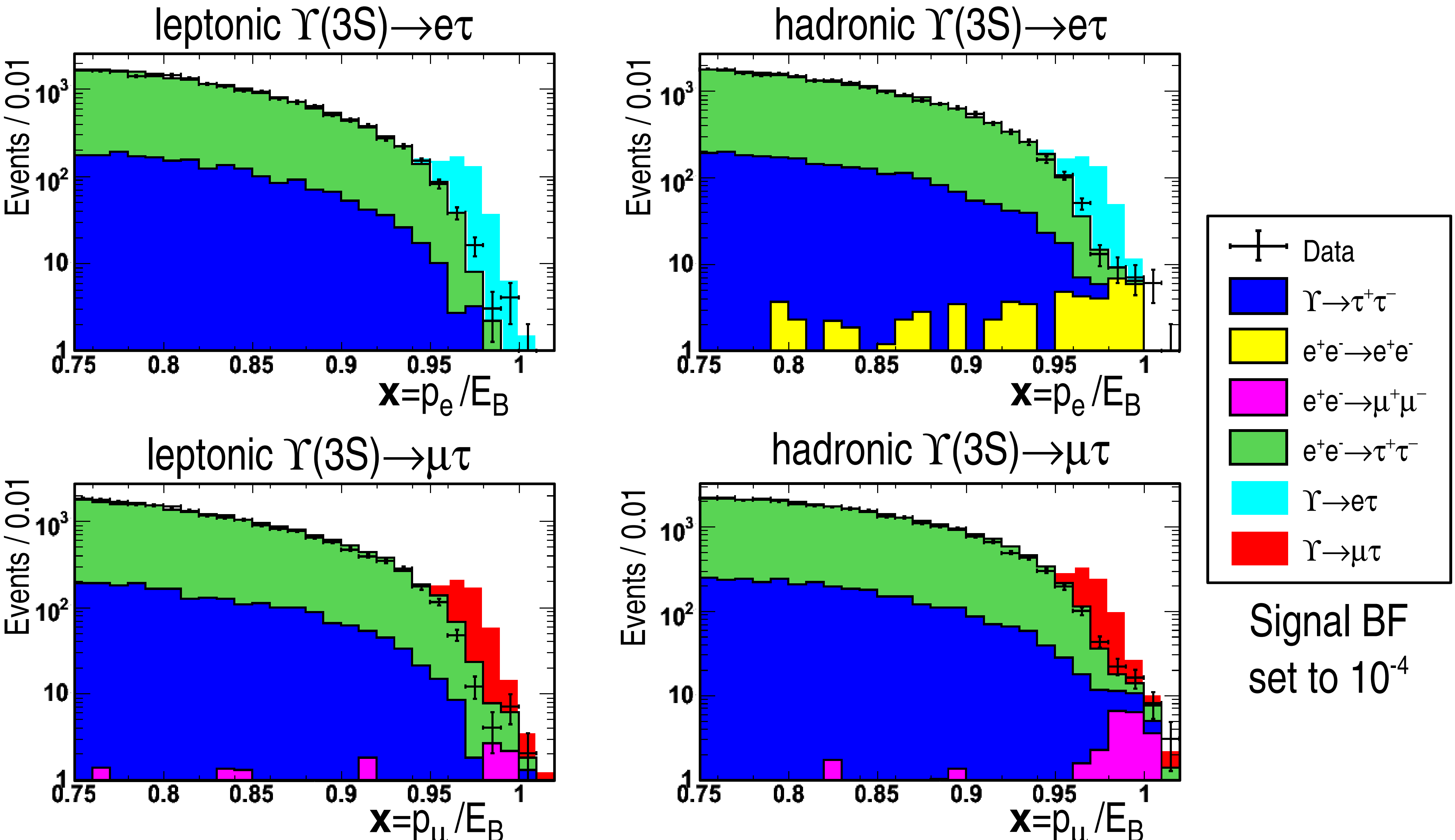
Channel-Specific Selection

Quantity		leptonic $e\tau$	hadronic $e\tau$	leptonic $\mu\tau$	hadronic $\mu\tau$
Particle ID Requirements		$1e+1\mu$	$1e+1\pi^{\pm}$ + 1 or 2 π^{0}'s	$1e+1\mu$	$1\mu+1\pi^{\pm}$ + 1 or 2 π^{0}'s
primary lepton momentum	$p_{e/\mu}/E_B$	$p_e/E_B>0.75$	$p_e/E_B>0.75$	$p_\mu/E_B>0.75$	$p_\mu/E_B>0.75$
τ-daughter transverse momentum	p_{T2}/EB		>0.05		
τ-daughter momentum	p_2/E_B		<0.8		<0.8
difference btw track CM azimuthal angles	$\Delta\phi^{CM}$			**$<172^\circ$**	
#IFR hits associated to τ-daughter	$nIFR_2$	**>3**			
mass of $\pi^{\pm}\pi^{0}$ system	$M(\pi^{\pm}\pi^{0})$		0.4-1.1 GeV/c^2		0.4-1.1 GeV/c^2
mass of $\pi^{\pm}\pi^{0}\pi^{0}$ system	$M(\pi^{\pm}\pi^{0}\pi^{0})$		0.6-1.5 GeV/c^2		0.6-1.5 GeV/c^2

Signal Efficiencies and Background Rates

Signal Efficiency (includes τ BF)	$\varepsilon_{SIG}(\%)$	4.72 ± 0.05	4.94 ± 0.06	4.16 ± 0.05	6.21 ± 0.06
Number of MC Events	N_{MC}	18966 ± 100	20524 ± 101	19995 ± 100	29087 ± 119
Number of Data Events	N_{DATA}	18720	20548	19966	27479

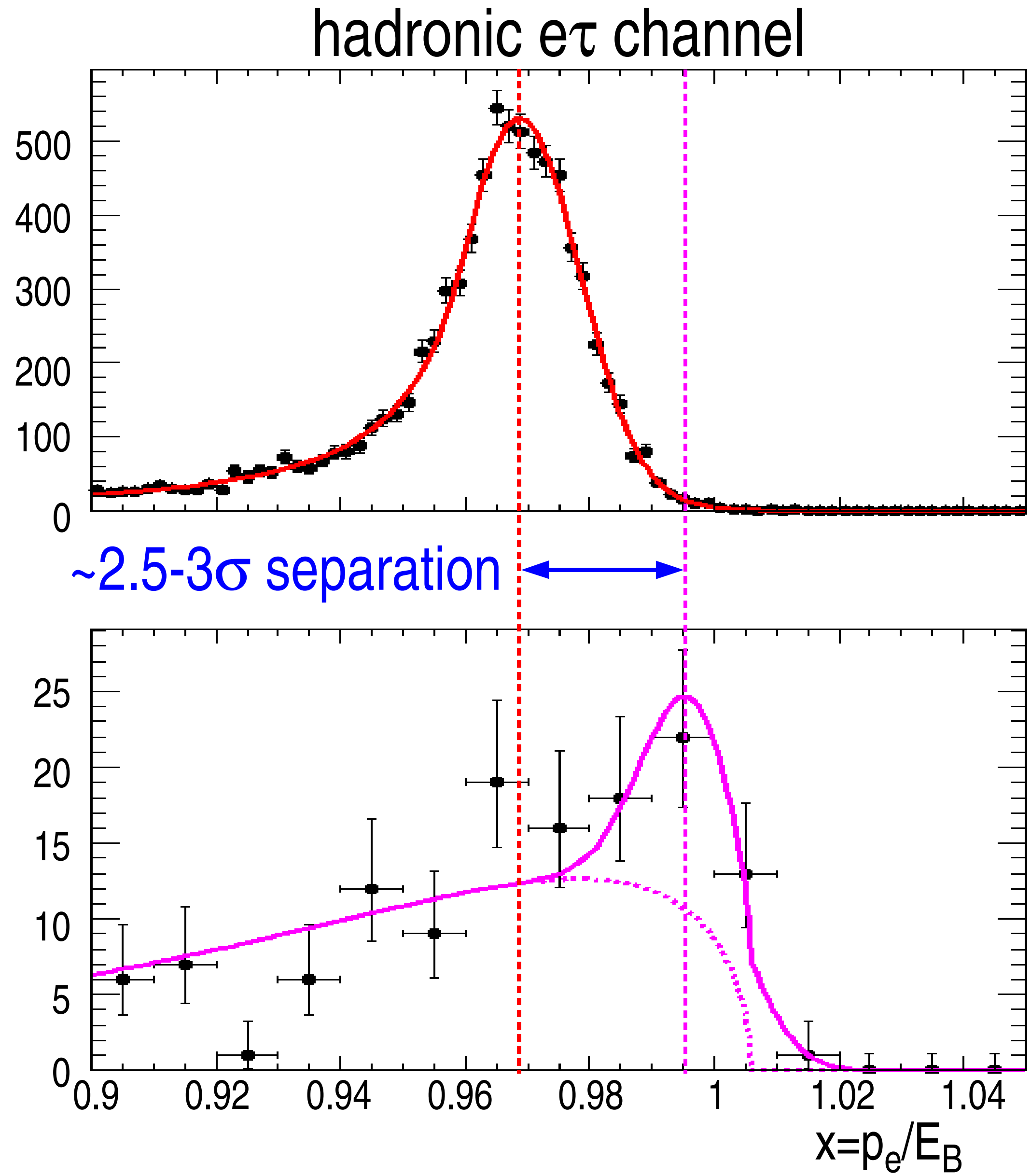
$\Upsilon(3S)$ Data/Monte Carlo Comparison



Signal BF set to 10^{-4}

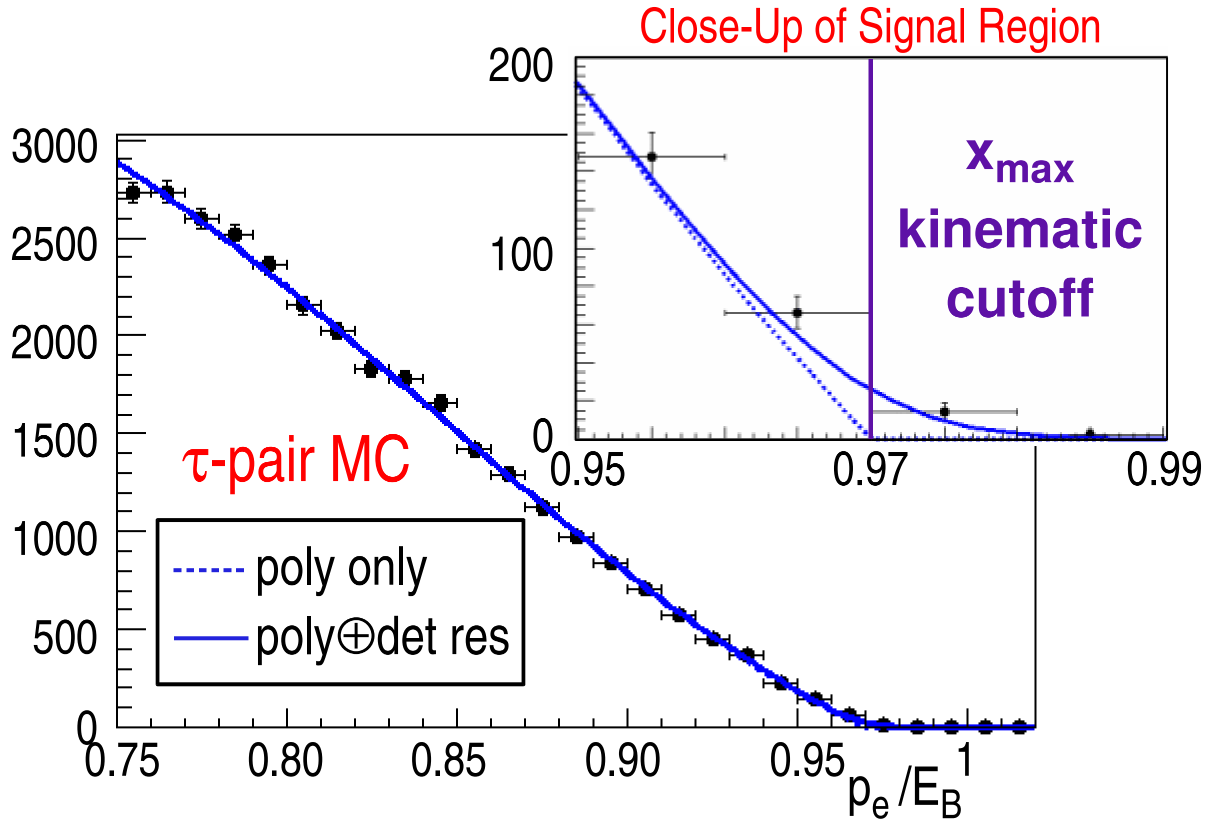
Signal and Reducible Bkg PDF's

- Extract PDF shapes from fits to MC
- **Signal PDF**
  - Double-sided Crystal Ball function peaked at 0.97, width ≈ 0.01
  - Radiative tail, especially eτ channels
- **Bhabha/μ-pair PDF**
  - Threshold function (Argus function) truncating at ~1 + Gaussian peaked at ~1, width ≈ 0.01



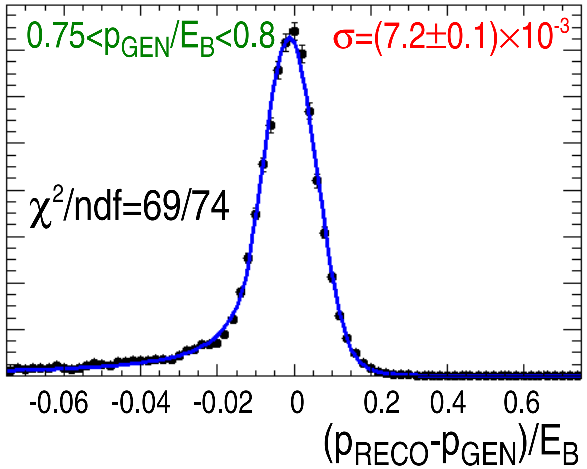
τ-Pair Background

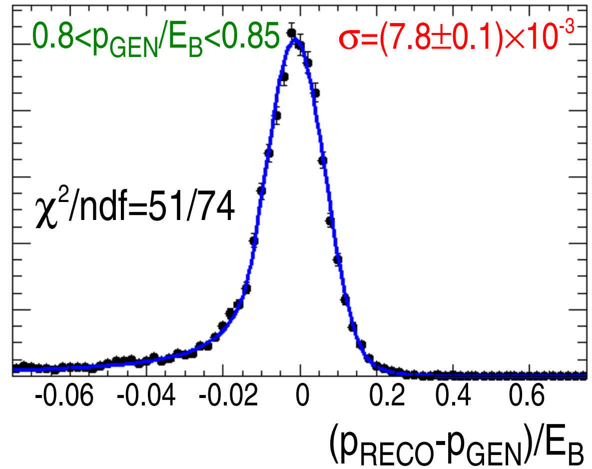
- High momentum tail of τ-pair background extends into signal region
- τ-pair PDF = (poly with **kinematic cutoff**) ⊕ (detector p_l resolution function)
- Step 1: Extract detector p_l resolution function from τ-pair Monte Carlo
- Step 2: Extract **kinematic cutoff** from fit to ϒ(4S) data control sample (no signal)

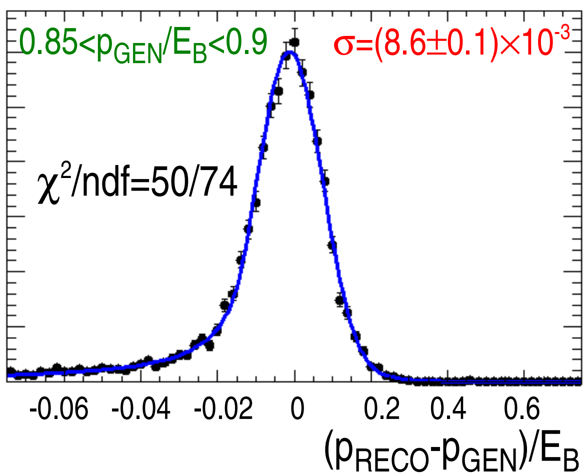


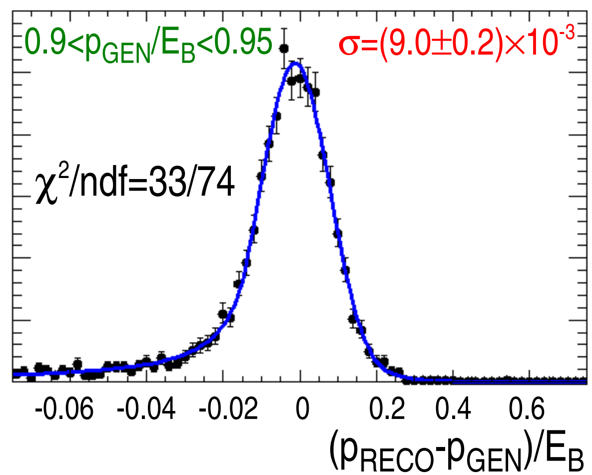
Extraction of Detector p_l Resolution Function

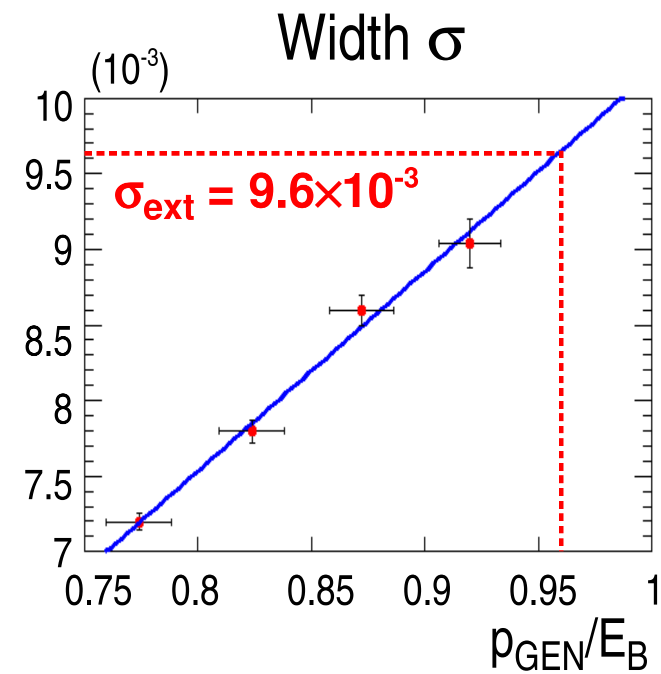
- Split τ-pair MC into 4 bins of p_{GEN} = generated lepton momentum. Fit double CB function to each distribution of $(p_{RECO}-p_{GEN})/E_B$ with floated σ, all other parameters of double CB common.
- Extrapolate width to $p_{GEN}/E_B = 0.96$, ~1σ to the left of the kinematic cut-off.





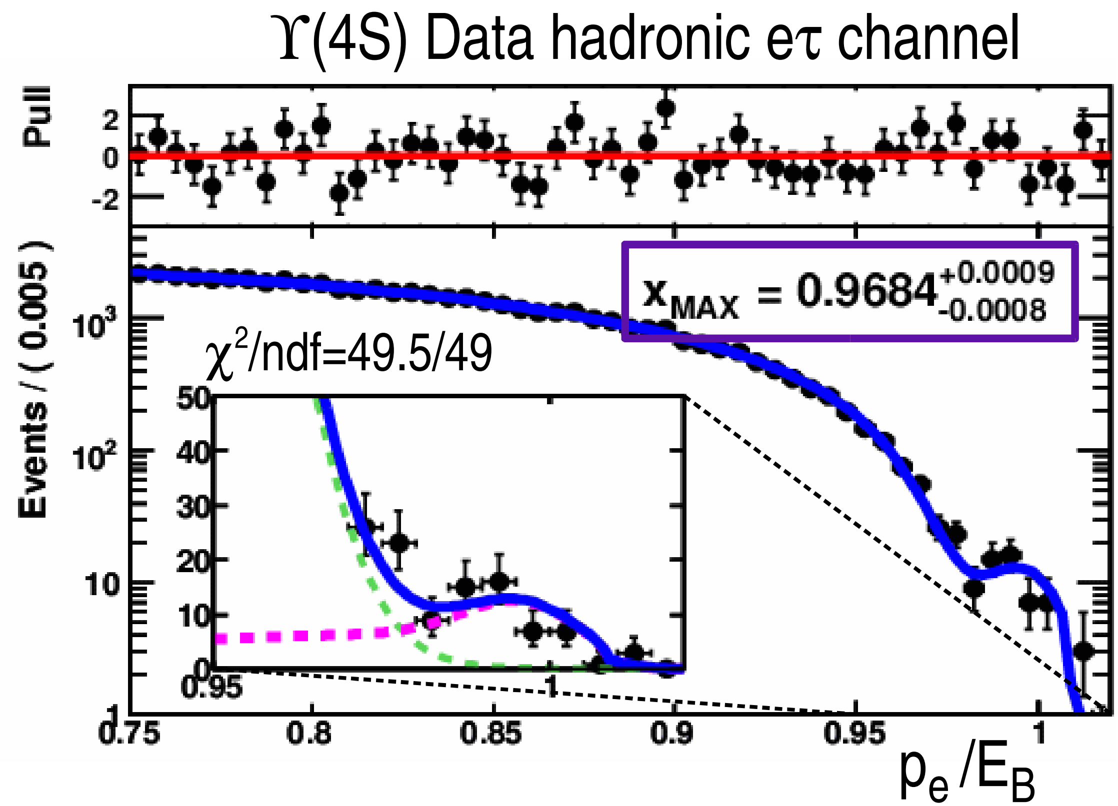






Extraction of Kinematic Cutoff

- Fix signal yield to zero, fit to $\Upsilon(4S)$ data using τ-pair PDF+bhabha PDF
- Extract **kinematic cutoff x_{max}**
- Validate extracted τ-pair PDF using fits to data control samples with signal yield floated. Extracted signal yield is consistent with zero.

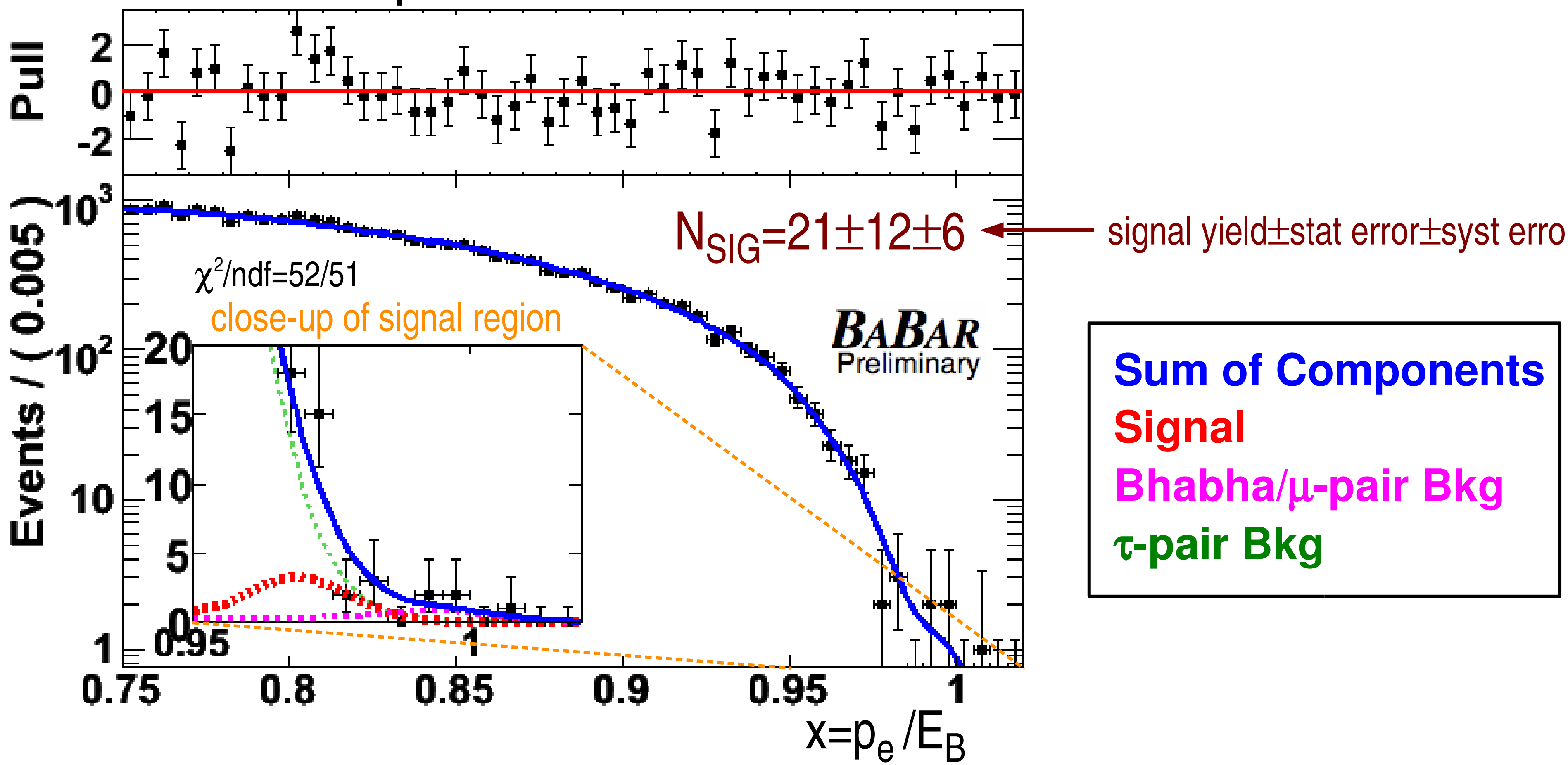


Channel	25.9 fb^{-1} $\Upsilon(4S)$ On-Peak	2.6 fb^{-1} $\Upsilon(3S)$ Off-Peak	1.2 fb^{-1} $\Upsilon(3S)$ On-Peak
leptonic $e\tau$	1.7 ± 8.8	0.1 ± 2.2	-2.2 ± 1.7
hadronic $e\tau$	18 ± 13	6.7 ± 5.3	-0.3 ± 2.3
leptonic $\mu\tau$	14 ± 10	-1.9 ± 2.7	2.9 ± 3.1
hadronic $\mu\tau$	6 ± 12	-4.6 ± 3.3	-7.7 ± 2.6*

Maximum Likelihood Fit Strategy

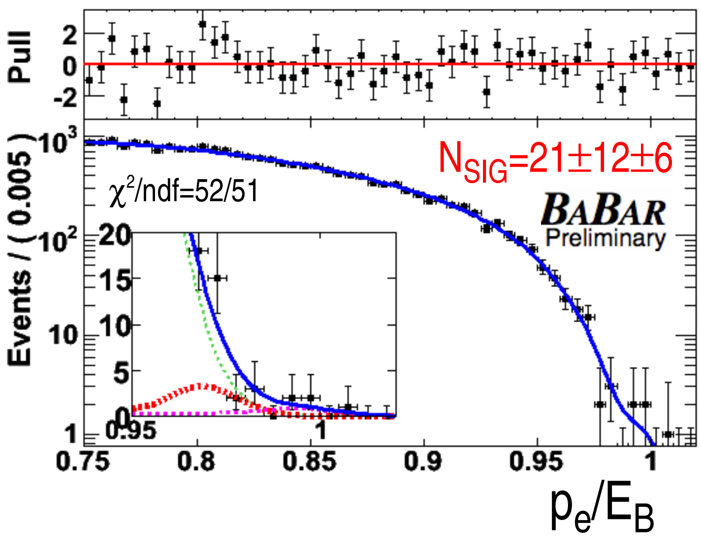
- Perform unbinned, extended maximum likelihood fit to x distribution
- Global PDF = sum of components: signal + τ-pair + bhabha (μ-pair) for eτ (μτ) channels
- Yields of components floated and extracted by fit

leptonic eτ channel

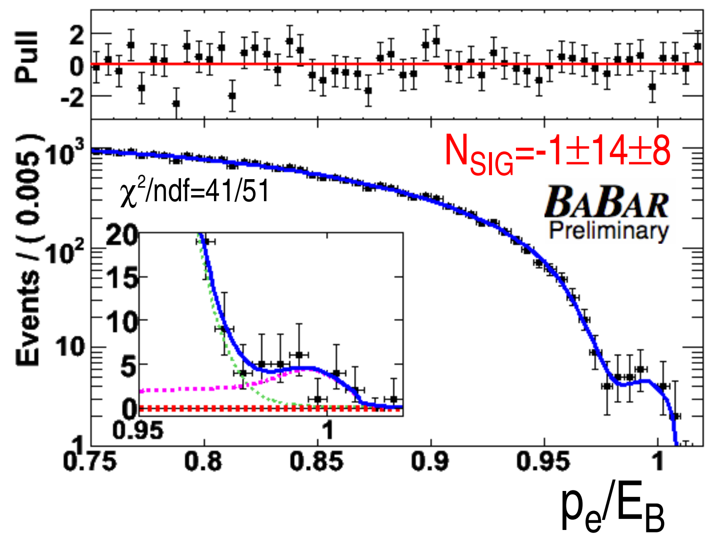


ϒ(3S) Data Fit Results

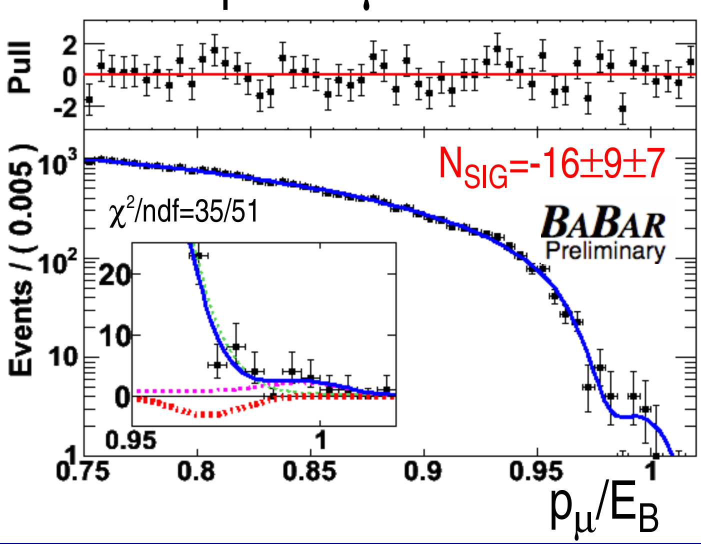
leptonic eτ channel



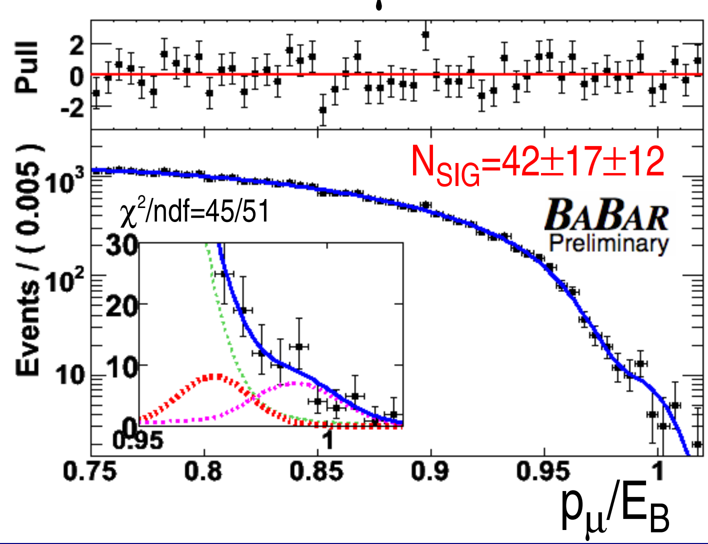
hadronic eτ channel



leptonic μτ channel



hadronic μτ channel



Sum of Components
Signal
τ-pair Bkg
Bhabha/μ-pair Bkg

Channel	Significance
leptonic eτ	+1.6σ
hadronic eτ	-0.05σ
leptonic μτ	-1.3σ
hadronic μτ	+2.1σ

All channels consistent with zero signal yield

Determination of Systematic Uncertainties

- **N_{SIG}: signal yield extracted by ML fit**
  - Dominant contribution from PDF shape uncertainties
  - Potential bias in fit procedure

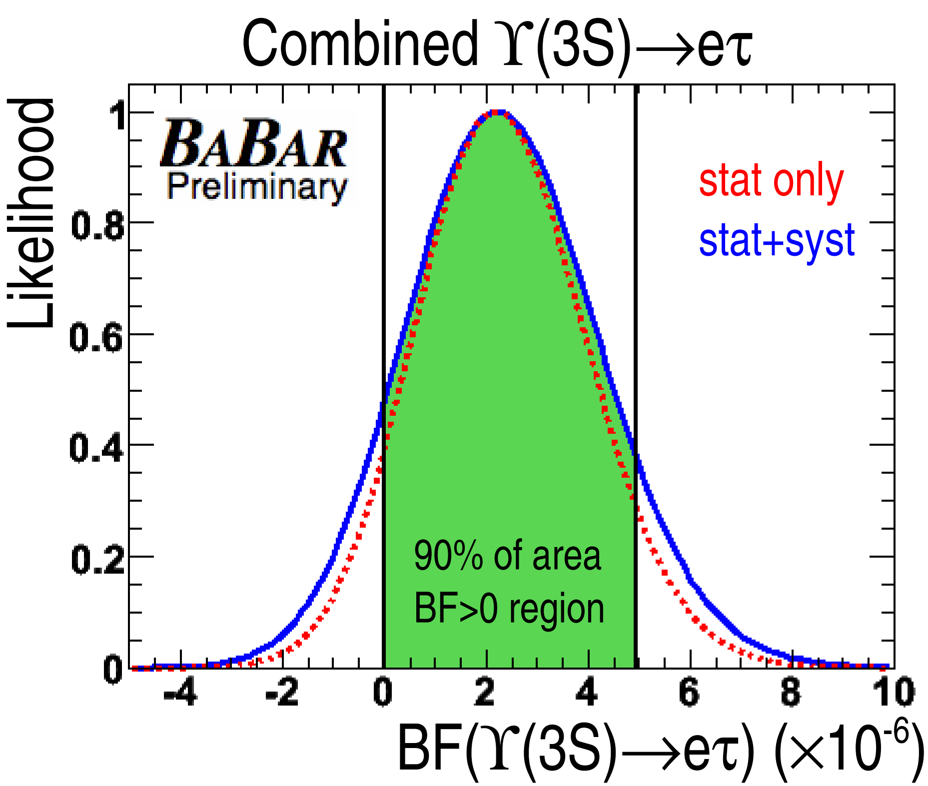
$$BF = \frac{N_{SIG}}{\varepsilon_{SIG} \times N_{\Upsilon(3S)}}$$

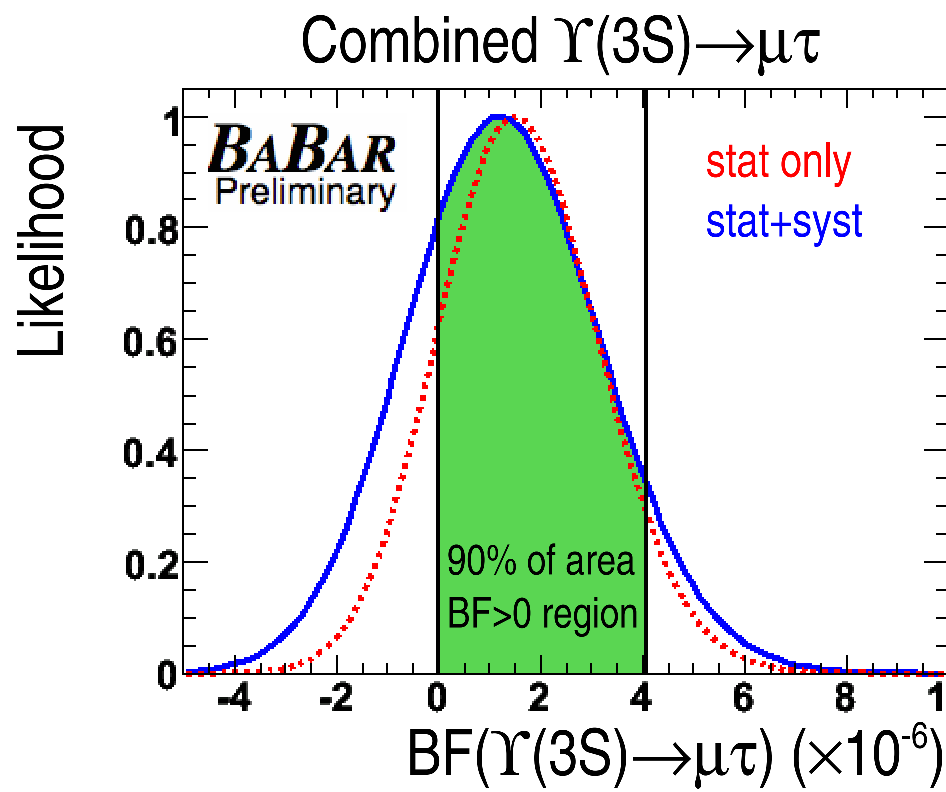
- **ε_{SIG}: signal efficiency**
  - ε_{SIG} calculated from MC. Take data/MC yield ratio for τ-pair sample from sideband of x distribution
- **$N_{\Upsilon(3S)}$: number of collected $\Upsilon(3S)$ decays**
  - Measure $N_{\Upsilon(3S)}$ by measuring multi-hadron event rates

Quantity	leptonic $e\tau$	hadronic $e\tau$	leptonic $\mu\tau$	hadronic $\mu\tau$
PDF Shapes	5.8 events	8.2 events	6.7 events	11.5 events
Fit Bias	1.6 events	1.3 events	0.8 events	1.3 events
ε_{SIG}	2.0%	3.2%	2.2%	1.0%
$N_{\Upsilon(3S)}$	1.0%	1.0%	1.0%	1.0%

CLFV Branching Fraction Upper Limits

Perform likelihood scan to extract 90% CL upper limits





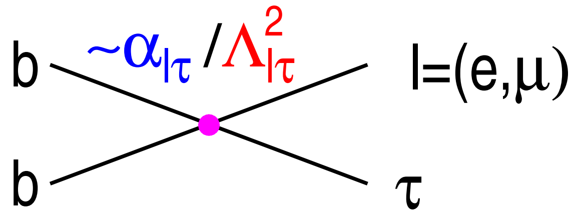
$BF(\Upsilon(3S)\rightarrow e\tau) < 5.0\times10^{-6}$

$BF(\Upsilon(3S)\rightarrow \mu\tau) < 4.1\times10^{-6}$

(first upper limit) BaBar arXiv.0812.1021 (>4x better than previous UL)

NP Limits from Effective Field Theory

CLFV Υ decays$\rightarrow$ 4-fermion contact interaction with NP coupling constant and mass scale

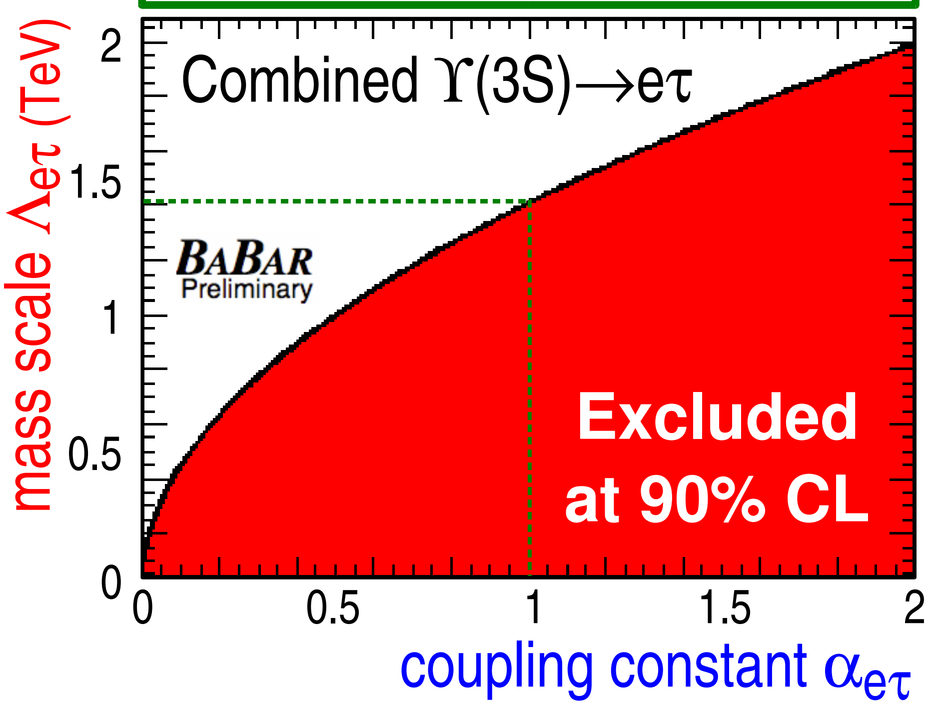


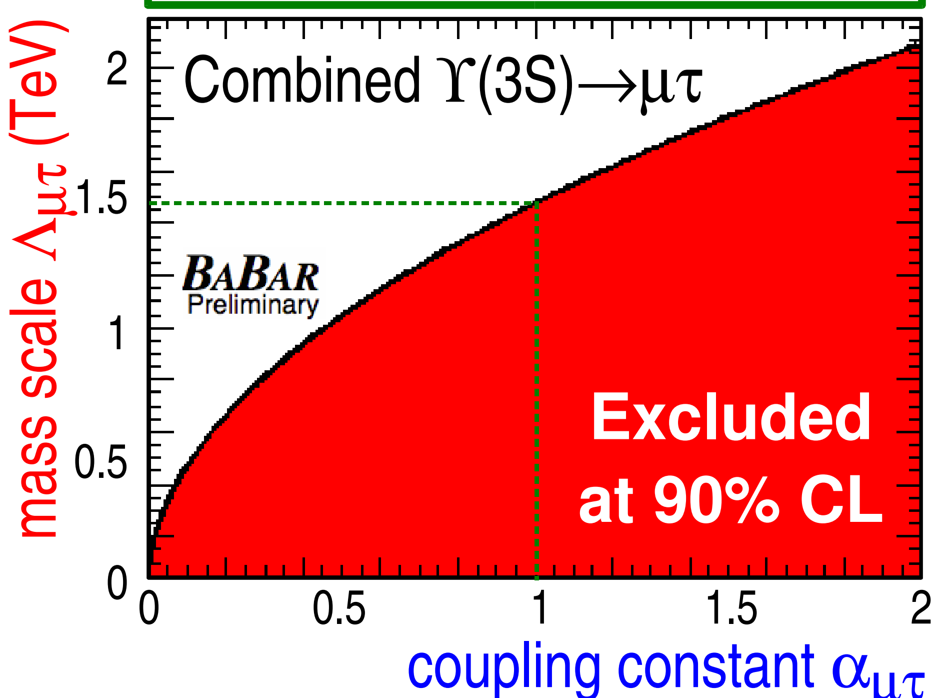
$$\frac{\alpha^2_{l\tau}}{\Lambda^4_{l\tau}} = \frac{BF(\Upsilon(3S)\rightarrow l\tau)}{BF(\Upsilon(3S)\rightarrow ll)} \frac{2q_b^2\alpha^2}{(M_{\Upsilon(3S)})^4} \quad l=(e,\mu)$$

Silagadze Phys. Scripta 64.128 & Black et al. PRD 66.053002

$\alpha_{e\tau} = 1 \rightarrow \Lambda_{e\tau} > 1.4$ TeV

$\alpha_{\mu\tau} = 1 \rightarrow \Lambda_{\mu\tau} > 1.5$ TeV





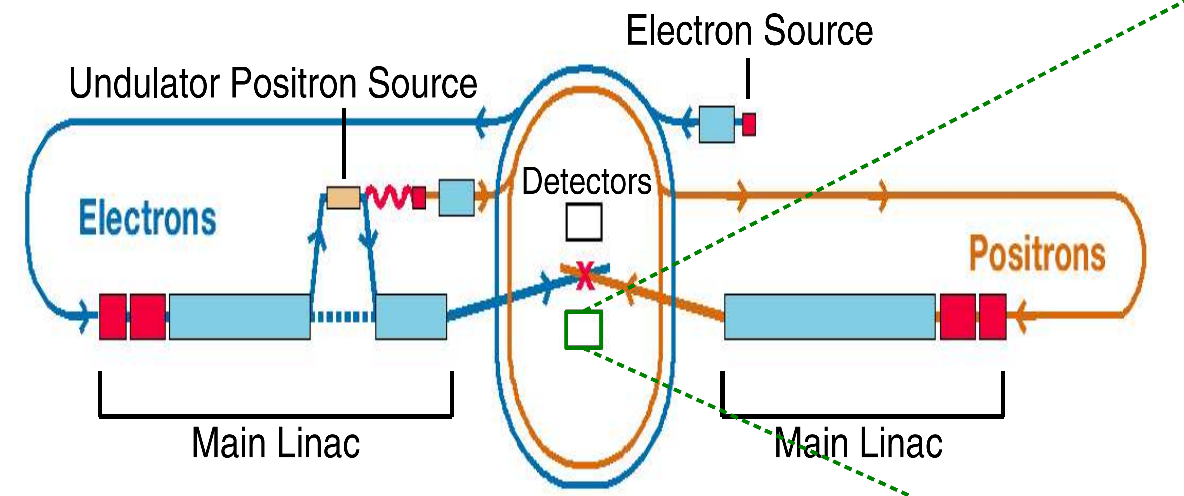
CLFV Preliminary Results and Outlook

- Performed 1st LFV search using BaBar $\Upsilon(3S)$ dataset
  - **BF($\Upsilon(3S) \to e\tau$) < 5.0×10^{-6}** (1st upper limit)
  - **BF($\Upsilon(3S) \to \mu\tau$) < 4.1×10^{-6}** (>4x improvement w.r.t. prior UL)
- Results probe new physics up to mass scale ~1.5 TeV
- Compelling new physics probe complementary to LHC
- More results soon to be available from $\Upsilon(2S)$ data

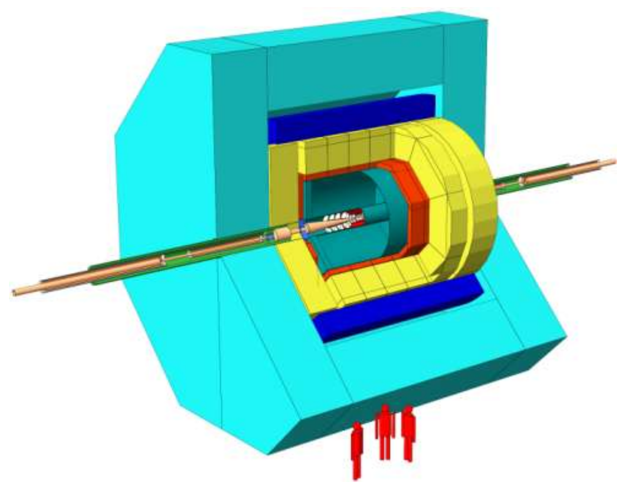
Table of Contents

Toward a Future Lepton Collider & Detector

- The **I**nternational **L**inear **C**ollider: e^+e^- collisions at tunable E_{CM} = 0.5 TeV, upgradeable to 1 TeV
- Complementary to LHC: precision measurements of Higgs profile, precision probe of new physics
- Detector R&D effort focus of world-wide study



Proposed ILC Layout

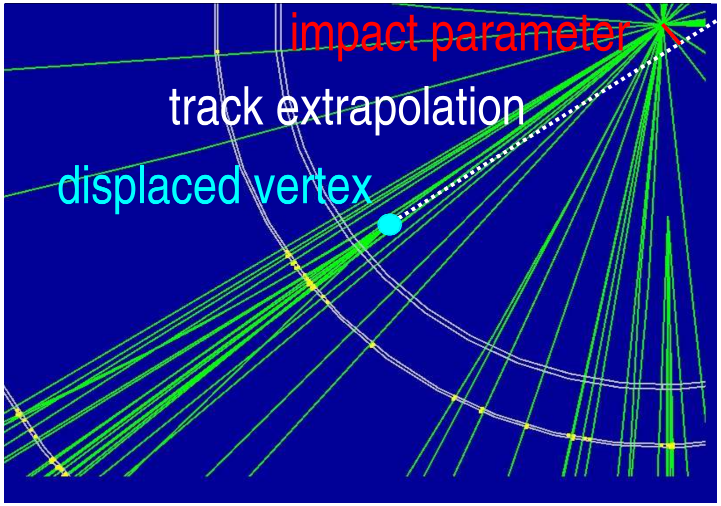


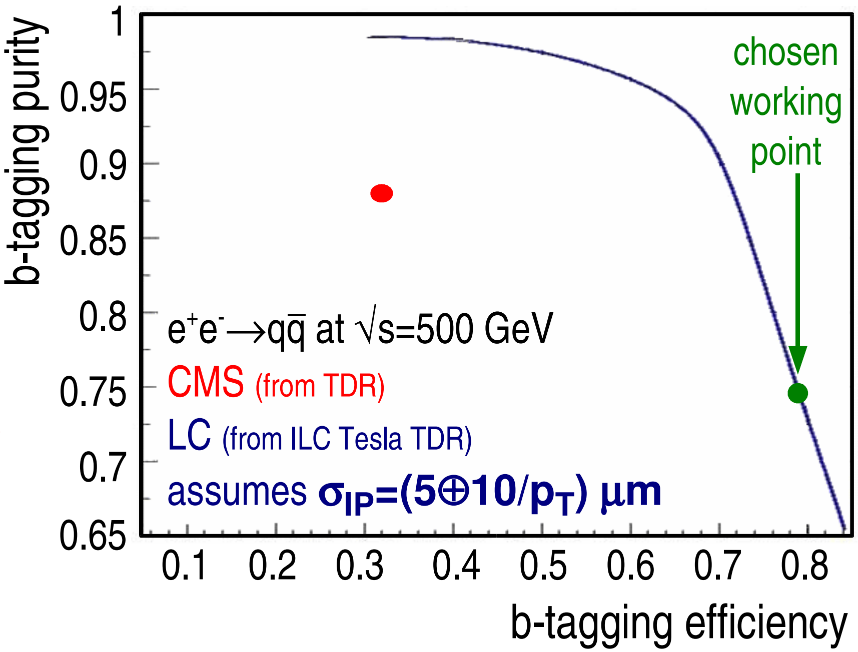
The Proposed **L**arge **D**etector **C**oncept

Si vertex detector, TPC tracker, Si-W EM calorimeter, RPC hadronic calorimeter, 4T solenoid

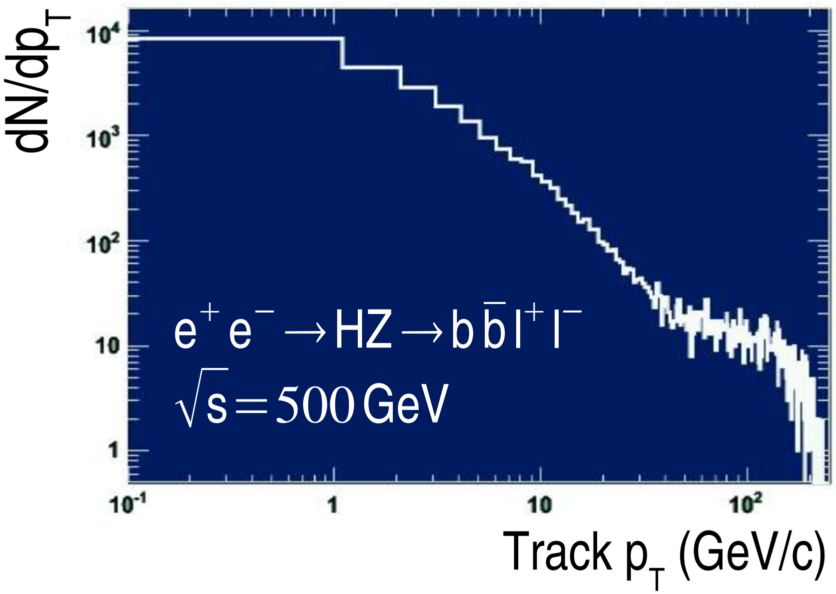
Vertex Tracking at a Future Lepton Collider

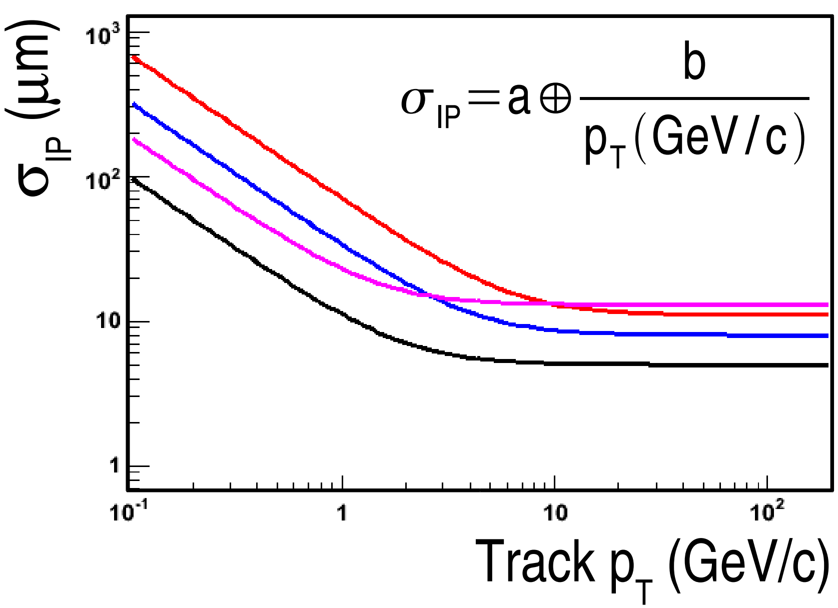
- VTX: innermost detector, concentric barrels of Si sensors for precise extrapolation to particle production points
- Identify tracks from displaced vertices from heavy, long-lived particles (ie. b, c, τ) using impact parameter $\rightarrow \sigma_{IP}$ determines efficiency
- Superb flavor-tagging capability required
  - Higgs BF's: $h \rightarrow b\bar{b}$ / $c\bar{c}$ / $\tau^+\tau^-$
  - Probe NP coupling preferentially to heavy flavors
  - **$H^0A^0 \rightarrow$ 4 b-jets: $\varepsilon_{SIG} \sim (\varepsilon_b)^4$ & $S/B \approx 10^{-4}$ $\rightarrow$need excellent b-tagging performance**





The Need for Thin Sensors



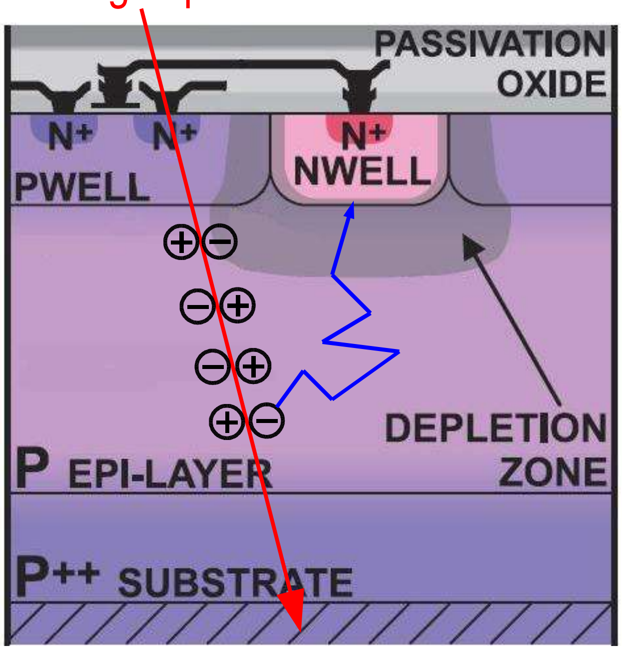


- At low p_T, σ_{IP} dominated by **M**ultiple **S**cattering $\to$ thin sensors required
- ILC Target 0.1% X_0 (~100 μm thick) modules: ~40-50μm Si sensors + support & cables
- Thickness directly related to flavor-tagging capability

	Constant Term a (μm)	MS Term b (μm)	Sensor Thickness (μm)
CMS	~10	~90	300
SLD	8	33	150
STAR (target)	13	19	50
ILC (target)	5	10	40-50

CMOS Pixel Sensors and Backthinning

charged particle

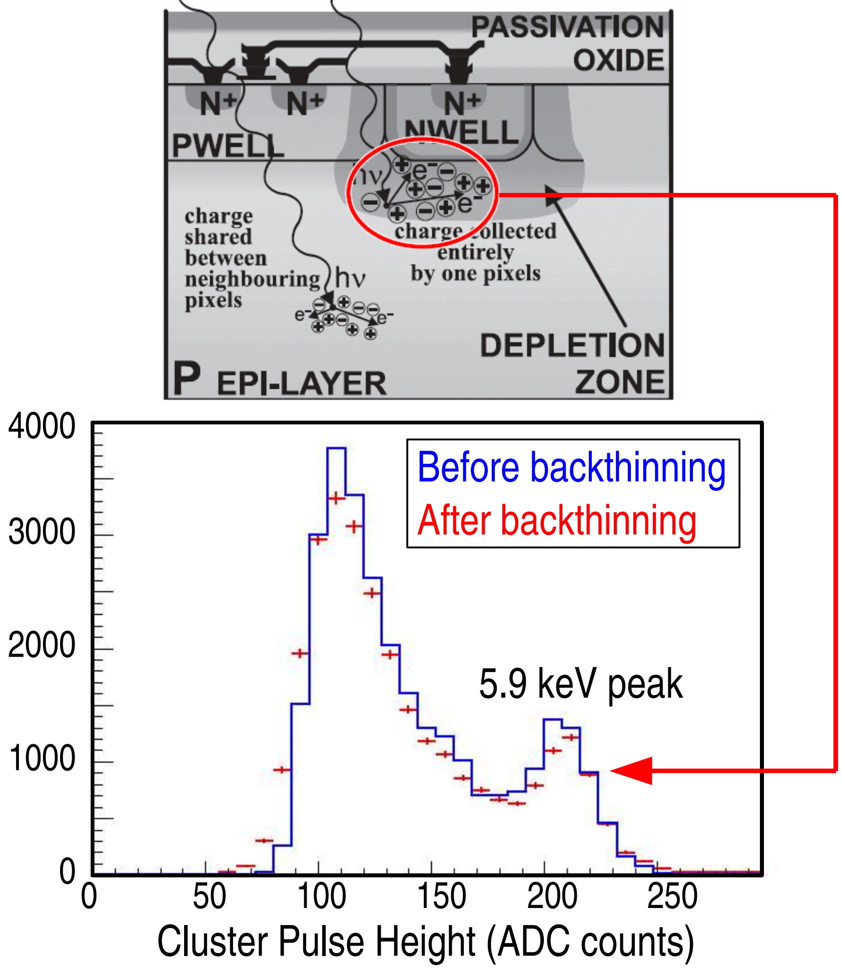


(not to scale) G. Deptuch

- **CMOS Pixel Sensors**
  - readout electronics + ~10-20 μm sensitive volume (p-doped epitaxial layer) integrated on ~300-500 μm bulk Si (P^{++}-doped substrate)
  - Charged particle generates e/h pairs in epi-layer
  - Electrons → n-doped potential wells (charge collection diodes) via thermal diffusion (no E-field, sensitive volume mostly undepleted)
- **Advantages**
  - No need for bump-bonding separate electronics and sensitive volume
  - Established commercial technology: widely available, cheap
  - Excellent spatial resolution, low noise, fast readout
  - **Charge generation confined to 10-20 μm epi-layer→ thin sensors possible**
- **Backthinning**
  - Remove majority of Si substrate using mechanical grind process
  - STAR: ~50 μm CMOS for HFT upgrade. Using thinned full Si wafers
  - Characterize individual sensors before/after thinning to assess effect on sensor performance

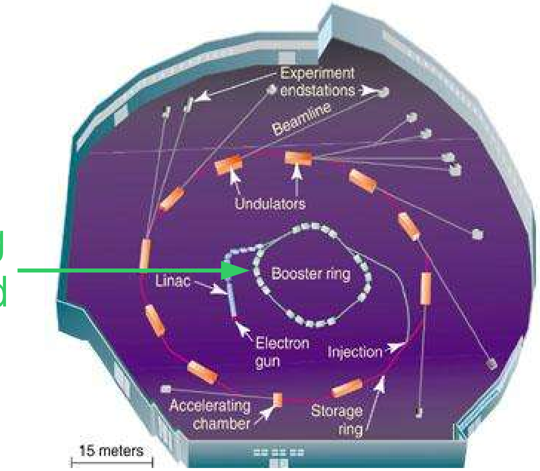
Backthinning Results

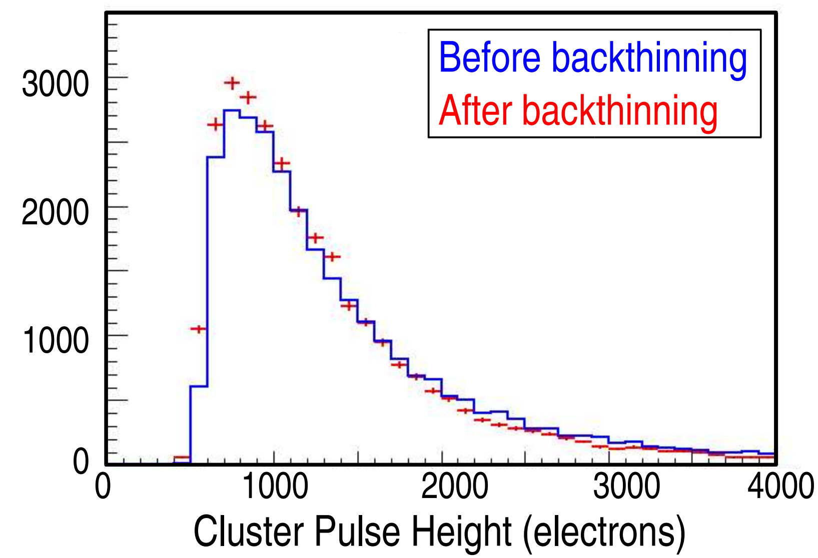
Energy Calibration with ^{55}Fe Source



1.5 GeV electron Test Beam

extract e$^-$ beam from booster ring of LBL Advanced Light Source



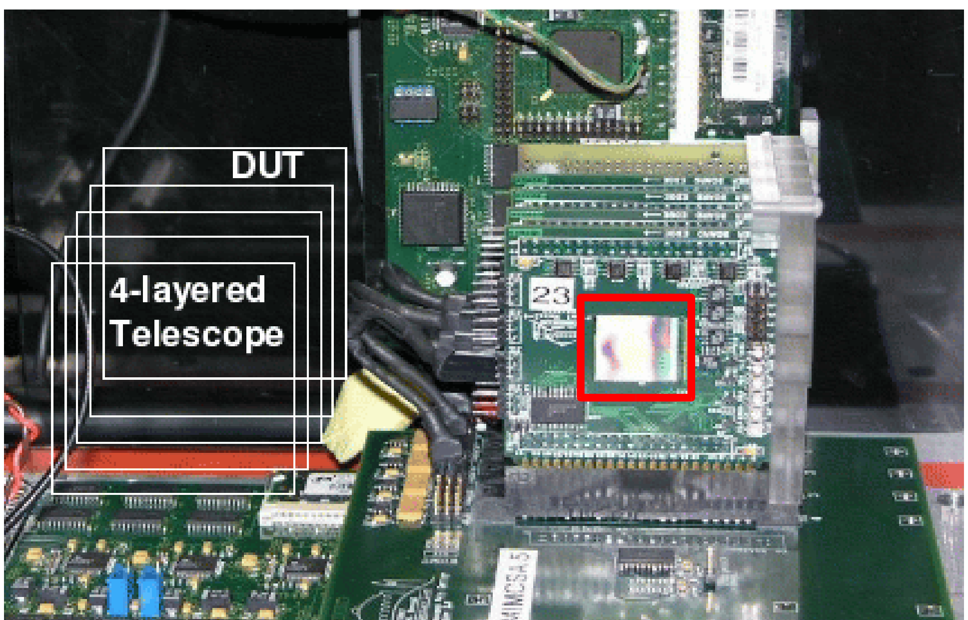


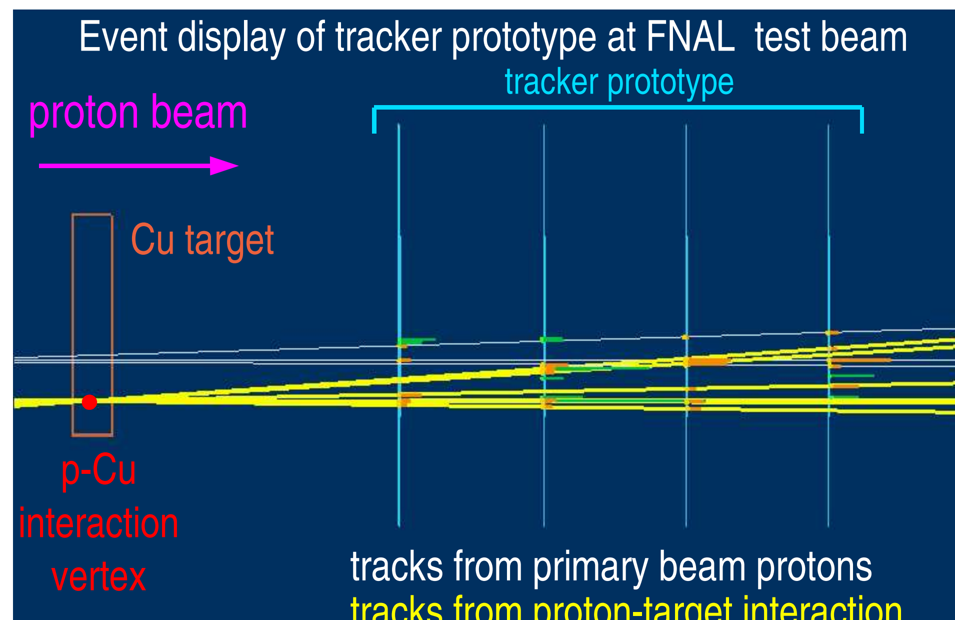
Feasibility of backthinning to required thickness without performance degradation demonstrated!

Hooberman with Battaglia et al. NIM A579.675-679

A Small-Scale Vertex Tracker Prototype with Thin Pixel Sensors

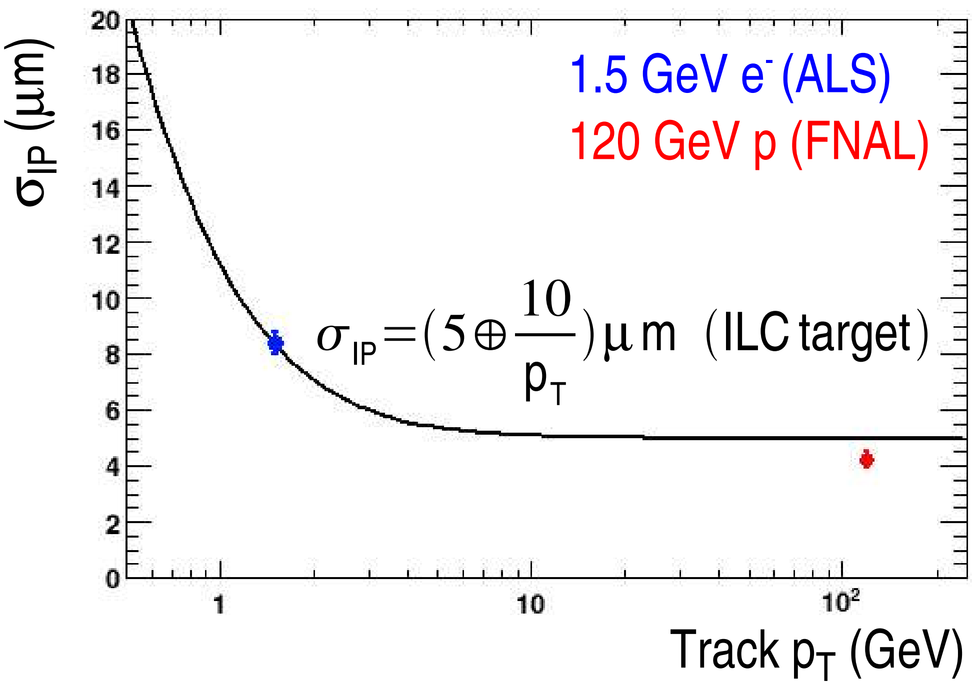
- Multiple planes of thinned CMOS pixel sensors: construct planar geometry tracker
- Perform tracking/vertexing studies with charged particle beams
  - Advanced Light Source: 1.5 GeV e^- test beam
  - Fermilab: 120 GeV p test beam

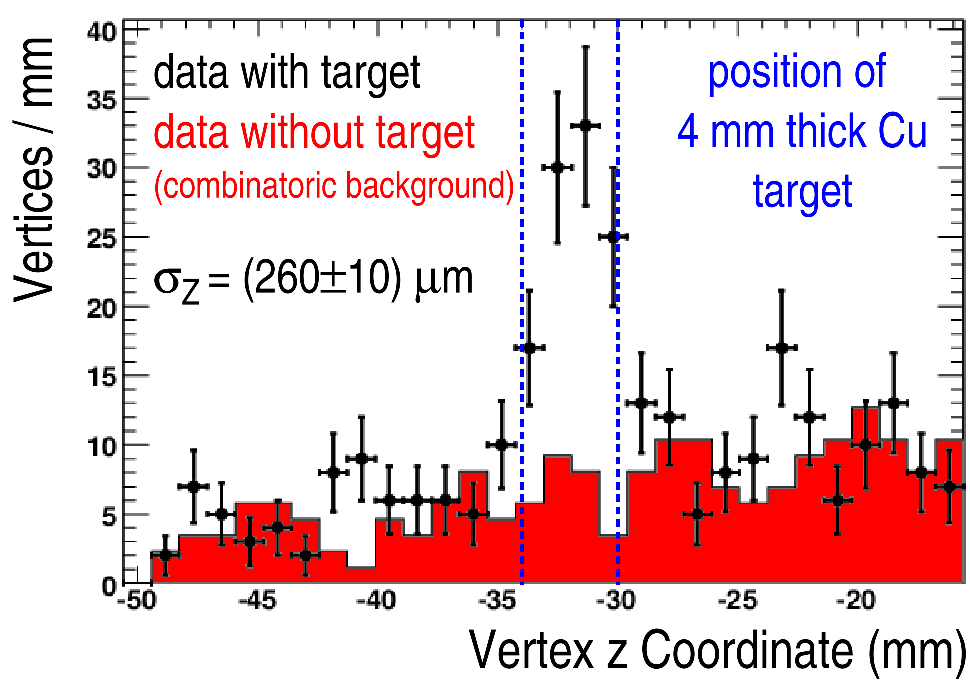




Tracker Prototype Performance

- Measured impact parameter resolution σ_{IP} at p_T=1.5 GeV, 120 GeV: **thinned CMOS tracker meets ILC σ_{IP} requirements!** →required b-tagging performance achievable.
- Reconstruct vertices from p-Cu interactions, plot vertex coordinate along flight direction (z). Measured longitudinal vertex resolution σ_Z consistent with ILC expectations.





Hooberman with Battaglia et al. NIM A593:292-297

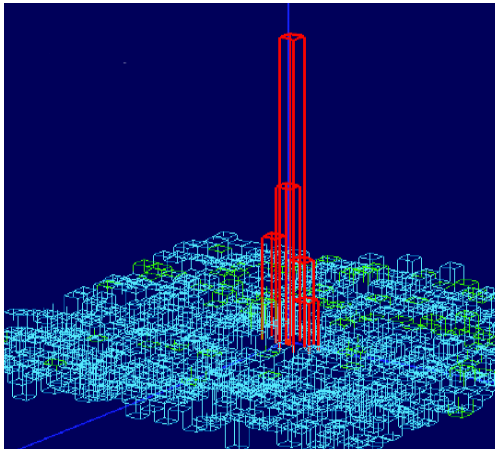
Table of Contents

- Introduction
- Probing TeV-scale physics with low energy data
  - Search for lepton-flavor violating decays at BaBar
- Detector R&D for a future TeV-scale lepton collider
  - R&D of thin sensors and construction of a vertex tracker prototype
- Searching for new physics at a TeV-scale lepton collider
  - Simulation studies of a dark-matter motivated Supersymmetry scenario

Detector R&D ↔ Physics Simulation+Reconstruction

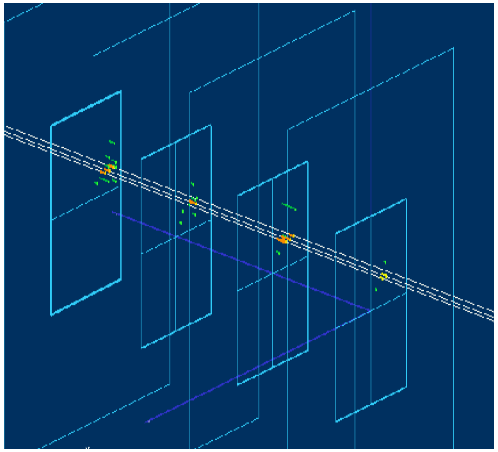
validate simulation with sensor/tracker data

extend simulation to full detector



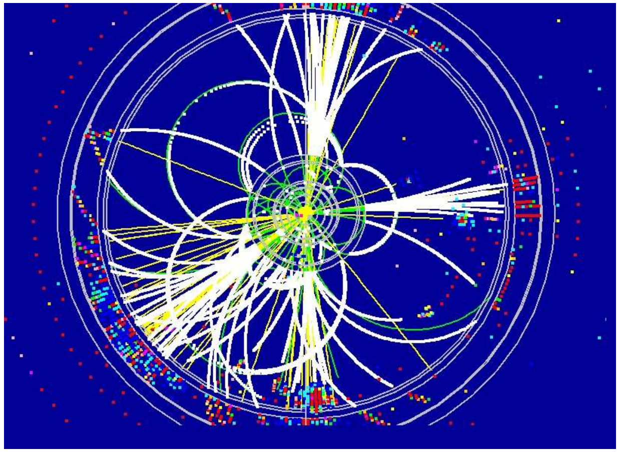
Single Sensor Simulation

→



Tracker Simulation

→

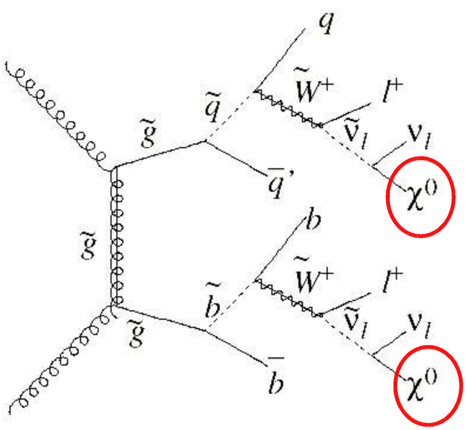


Full ILC Detector Simulation

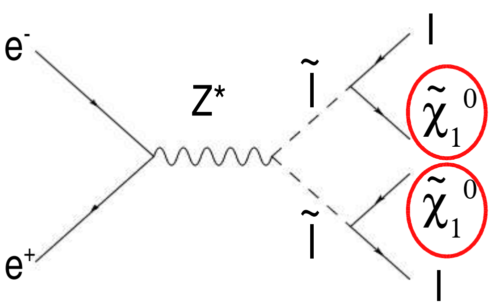
optimize detector design

- Use same GEANT + C^{++} Marlin framework for sensor, telescope, full detector simulation studies
- Excellent data/simulation agreement for sensor & telescope allows extension to study of full detector
- Investigate DM-motivated SUSY scenario at ILC 1 TeV

WIMP Dark Matter at Colliders



gluino pair production with cascade at LHC



slepton pair production at a future LC

- WIMP DM with M=O(10^2) GeV to be produced at TeV-scale colliders
- **Data can be used to predict Ω_{WIMP}!**
  - Assume WIMP DM produced thermally in early universe, left-over from near complete annihilation: $\Omega_{WIMP} \sim (\sigma_{ANN})^{-1}$
  - Collider data: measure properties of WIMP & particles coupling to it in early universe to determine $\sigma_{ANN} \rightarrow$ predict Ω_{WIMP}
- $\Omega_{WIMP}=\Omega_{DM} \rightarrow$ major breakthrough in understanding DM
- Choose benchmark point in which Ω_{WIMP} accuracy at LHC limited, determine accuracy on Ω_{WIMP} at 1 TeV ILC.

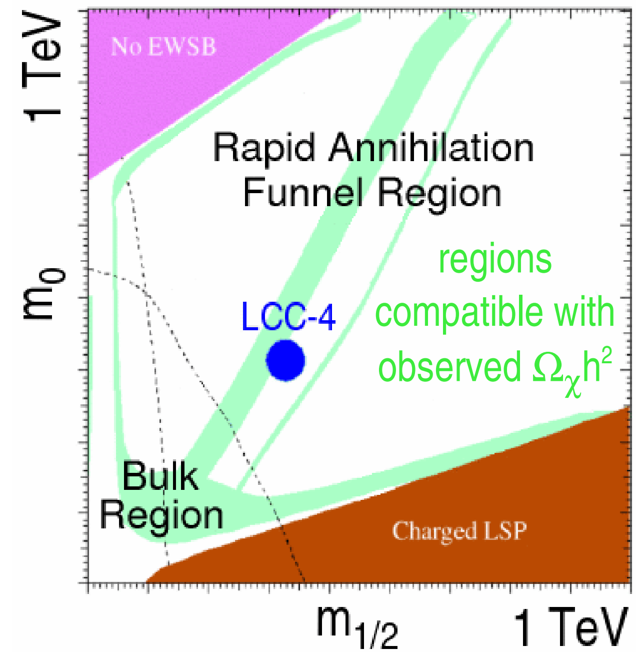
The Rapid Annihilation Funnel and $\Omega_\chi h^2$

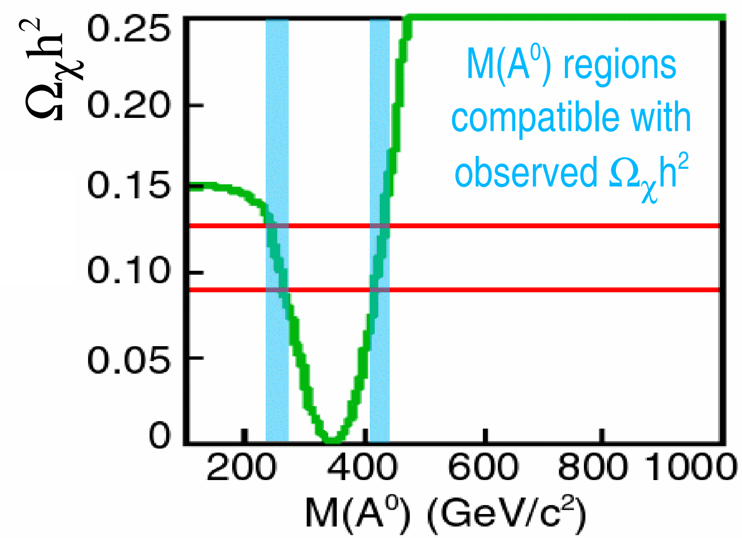
- mSUGRA: specific SUSY model defined by 5 parameters: m_0, $m_{1/2}$, $\tan\beta$, A, sign(μ)
- 5 Higgs particles: h^0, H^0, A^0, H^+, H^-
- The **LCC-4** benchmark point in rapid annihilation funnel region

m_0=380 GeV, $m_{1/2}$=420 GeV, A=0, $\tan\beta$=53, sign(μ)=+1, M_{top}=178 GeV	→	$M(A^0)$ = 419 GeV, $M(h^0)$=119 GeV, $M(\chi^0_1)$=169 GeV, $M(\tau_1)$=195 GeV

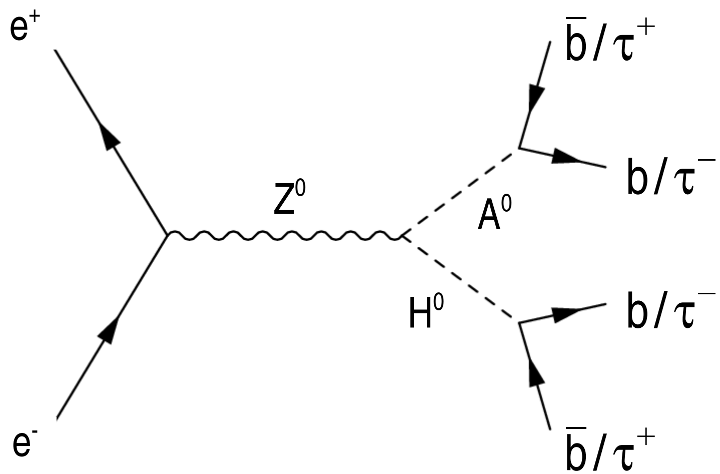
  - χ^0_1 LSP, $\Omega_\chi h^2$ determined by rate of $\chi\chi \rightarrow A^0 \rightarrow b\bar{b}/\tau^+\tau^-$
  - σ_{ANN} depends on $M(A^0)$, enhanced for $M(A^0) \approx 2M(\chi^0_1)$
  - ~10% uncertainty on $\Omega_\chi h^2$ requires ~0.5% uncertainty on $M(A^0)$
  - A^0 branching fractions also relevant for $\Omega_\chi h^2$

- **Goal of this analysis: measure A^0 properties using H^0A^0 production at ILC 1 TeV**





H^0A^0 Production at LCC-4



H^0/A^0 Properties at LCC-4

	CP	M (GeV)	Γ (GeV)	BR(X→bb)	BR(X→τ⁺τ⁻)
A^0	-	419.3	15.3	0.87	0.13
H^0	+	421.7	15.3	0.87	0.13

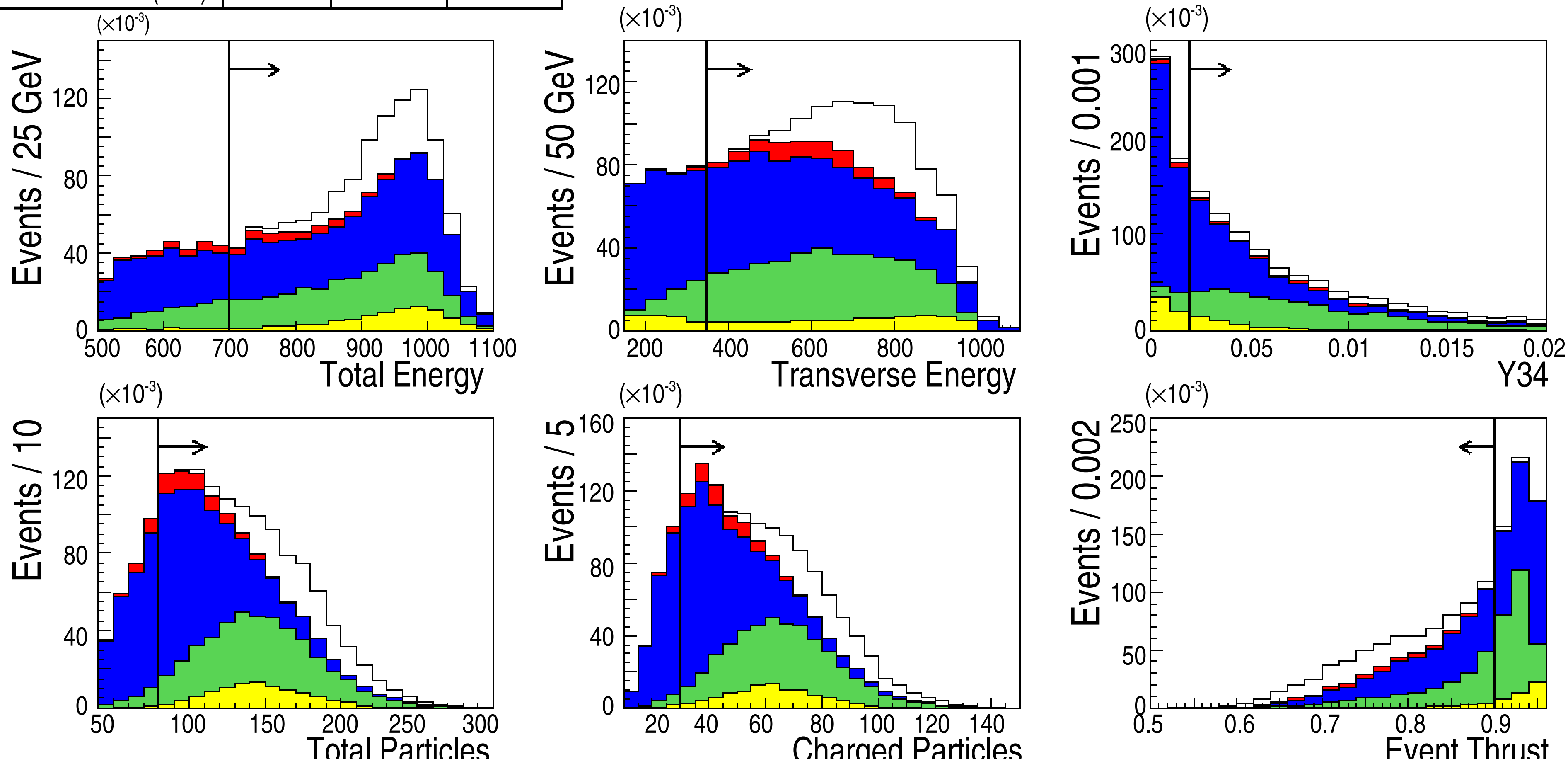
$\sigma(e^+e^-\to H^0A^0) = 1.4$ fb $\to$ 2800 events/2 ab^{-1} (~5 yrs)

- H^0, A^0 nearly degenerate in large M_A MSSM (de-coupling limit)
- H^0, A^0 discovery @ LHC, but mass resolution not sufficient for this analysis
- **$H^0A^0 \to b\bar{b}b\bar{b}$: reconstruct dijet masses to measure $M(A^0)$, $\Gamma(A^0)$**
- $H^0A^0 \to b\bar{b}\tau^+\tau^-$: constrain stau trilinear coupling A_τ to improve $\Omega_\chi h^2$ measurement

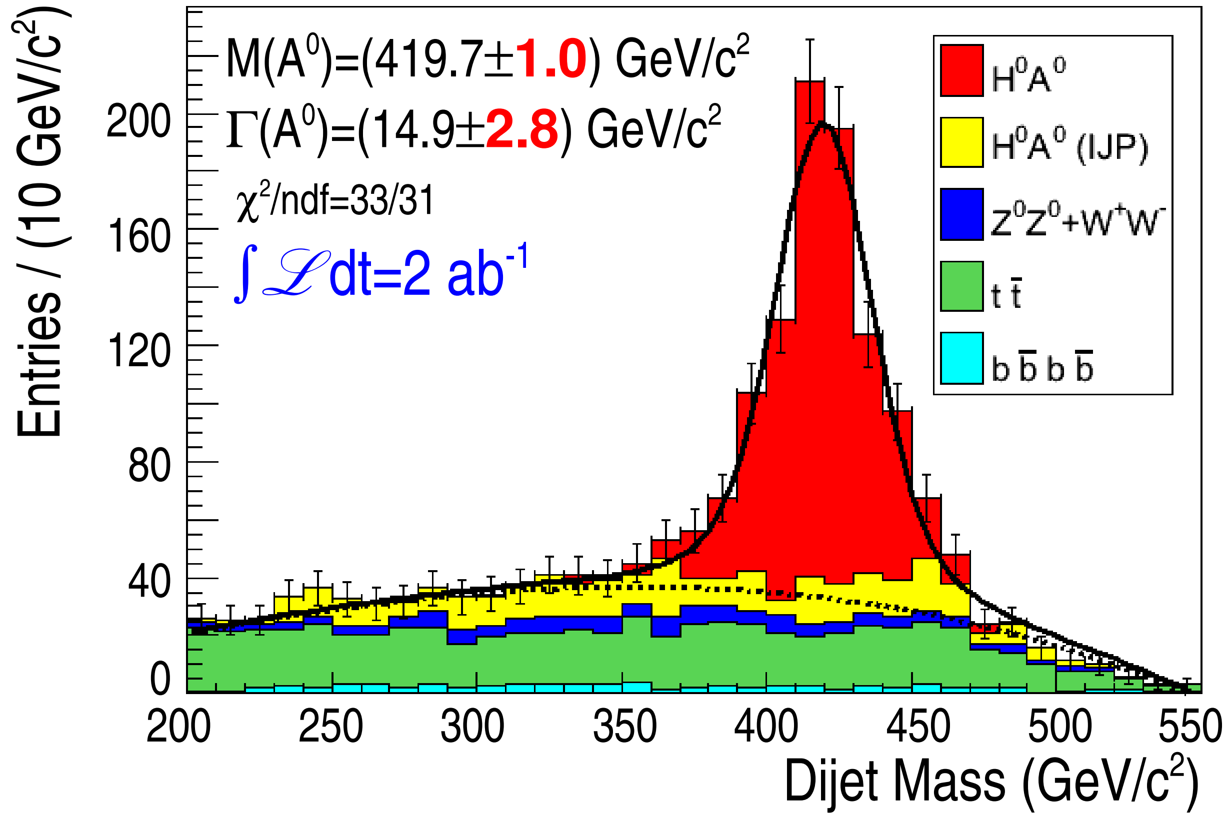
Kinematic Selection + b-Tagging

	Process	σ (fb)	ε(KIN)	ε(TOT)
	$H^0A^0 \to bbbb$ (×100)	1.0	0.93	0.24
(red)	$H^0A^0 \to bb\tau\tau$ (×100)	0.3	0.41	0
(blue)	$W^+W^- + Z^0Z^0$	3170	0.02	1×10^{-5}
(green)	tt	190	0.25	8×10^{-4}
(yellow)	inclusive bbbb (×10)	5.0	0.08	4×10^{-3}

- Kinematic selection alone not sufficient to suppress bkg
- Excellent b-tagging performance allows **4 b jet tags**
- Final selection (including b-tagging) suppresses bkg



$H^0 A^0 \rightarrow b\bar{b}b\bar{b}$ Results

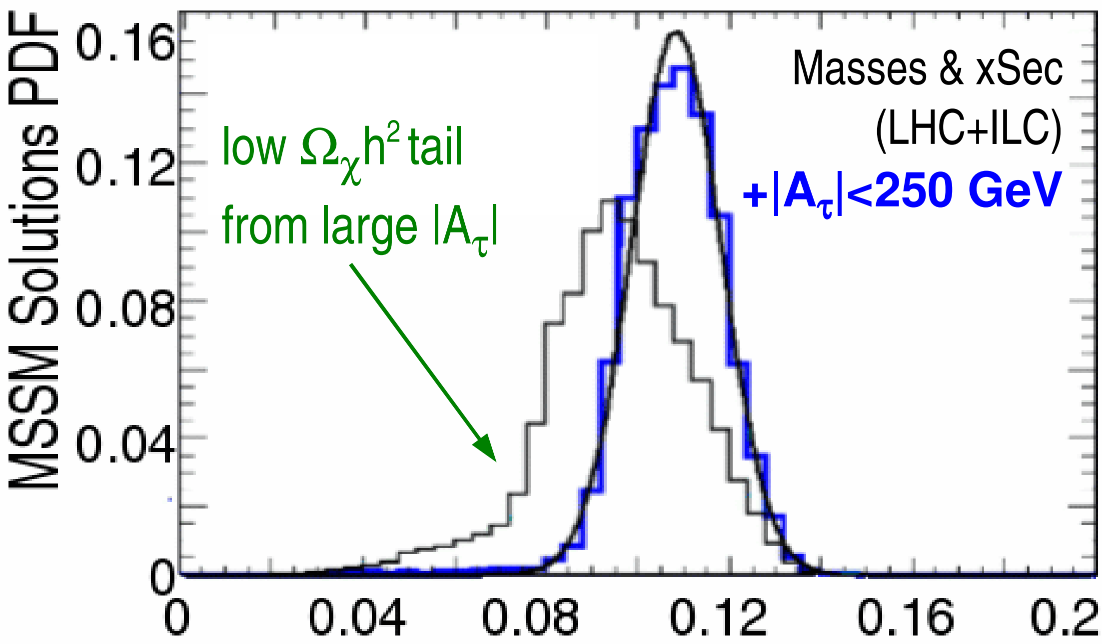


- Plot dijet masses (2 entries/event) using pairing which minimizes $|M_{JJ}^{(1)}-M_{JJ}^{(2)}|$
- Background: fit 3rd order polynomial to background MC + H^0A^0 events with incorrect jet pairing (IJP)
- Signal: 2 BW functions ⊕ Gaussian, σ_{GAUS} set to detector res, fix $M(H^0)-M(A^0)=1.4$ GeV & $\Gamma(H^0)=\Gamma(A^0)$
- Perform fit with $M(A^0)$, $\Gamma(A^0)$, signal and background yields floated
- **Required uncertainty on $M(A^0)$ achievable!**

Battaglia, Hooberman, Kelley. PRD 78.015021

Further Improvement of $\Omega_\chi h^2$ Measurement

$\Omega_\chi h^2$ in Full MSSM with H^0A^0 analysis



Baltz et al. hep-ph/0602187
Battaglia, Hooberman, Kelley. PRD 78.015021

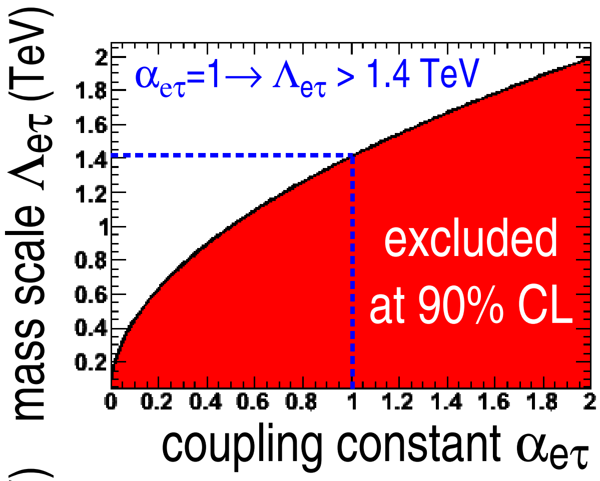
Assumed Measurements and Uncertainties

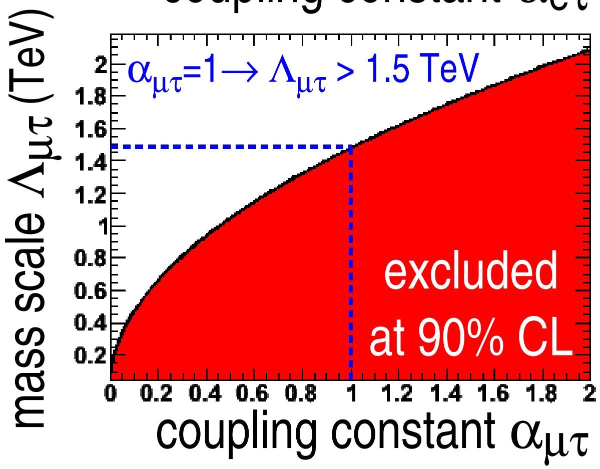
$M(A^0)$	419 ± 1.0 GeV/c^2
$\Gamma(A^0)$	14.9 ± 2.8 GeV/c^2
$BF(A^0 \to b\bar{b})$	0.87 ± 0.06
$BF(A^0 \to \tau^+\tau^-)$	0.13 ± 0.02
$M(\chi^0)$	169 ± 1.4 GeV/c^2

- Large $|A_\tau|$: $\chi\chi \to H \to \tilde{\tau}_1 \tilde{\tau}_1$ contributes to neutralino annihilation, reduces $\Omega_\chi h^2$
- $H^0A^0 \to b\bar{b}\tau^+\tau^-$ analysis yields **$|A_\tau|<250$ GeV**. Constraint eliminates low $\Omega_\chi h^2$ tail of PDF
- **$\Delta\Omega_\chi h^2/\Omega_\chi h^2 = 0.16 \to 0.08$ with $|A_\tau|$ constraint!**

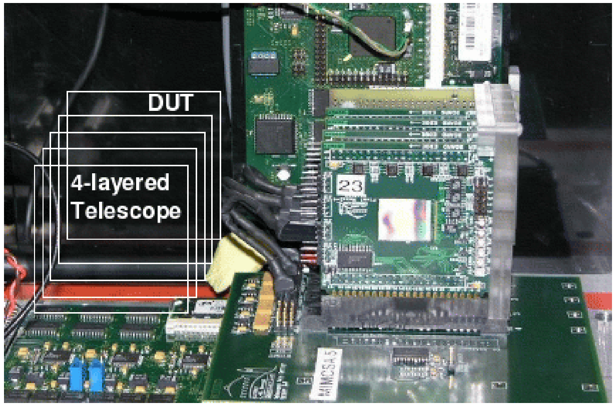
Conclusions

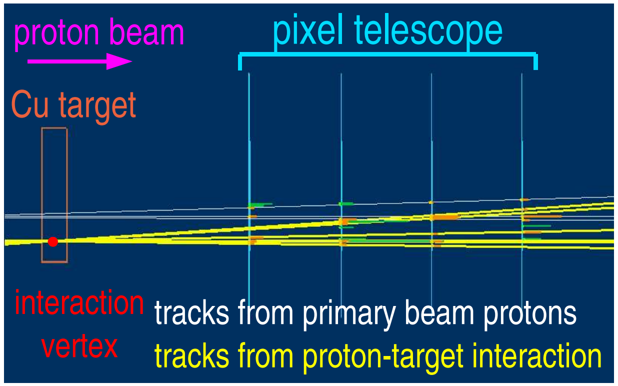
Can use precision effects at low energy to probe NP: search for CLFV Υ decays probes TeV-scale physics



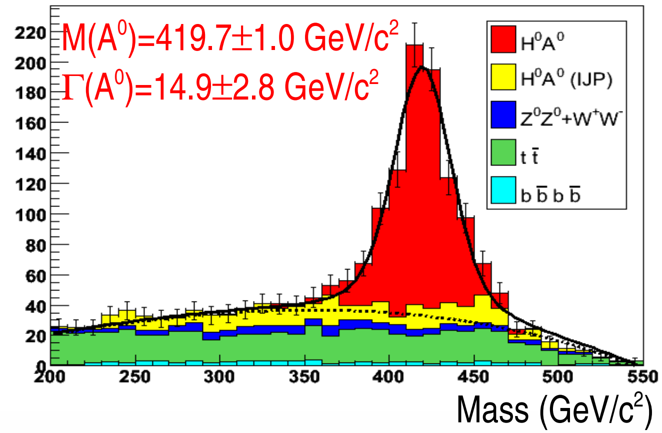


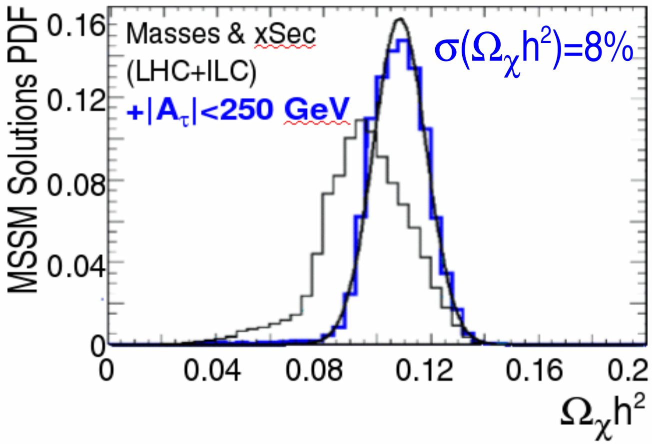
Need detector R&D studies to prepare for TeV-scale LC: built vertex-tracker prototype, performed tracking & vertexing





Can probe TeV-scale physics directly at future LC. Studies of H^0A^0 production significantly enhance accuracy on $\Omega_\chi h^2$

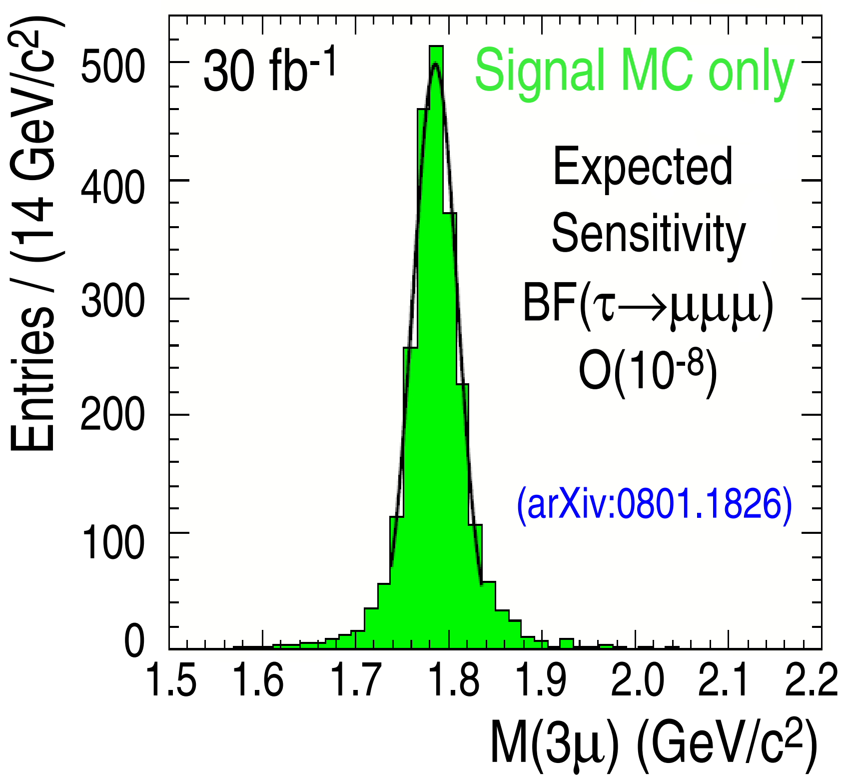




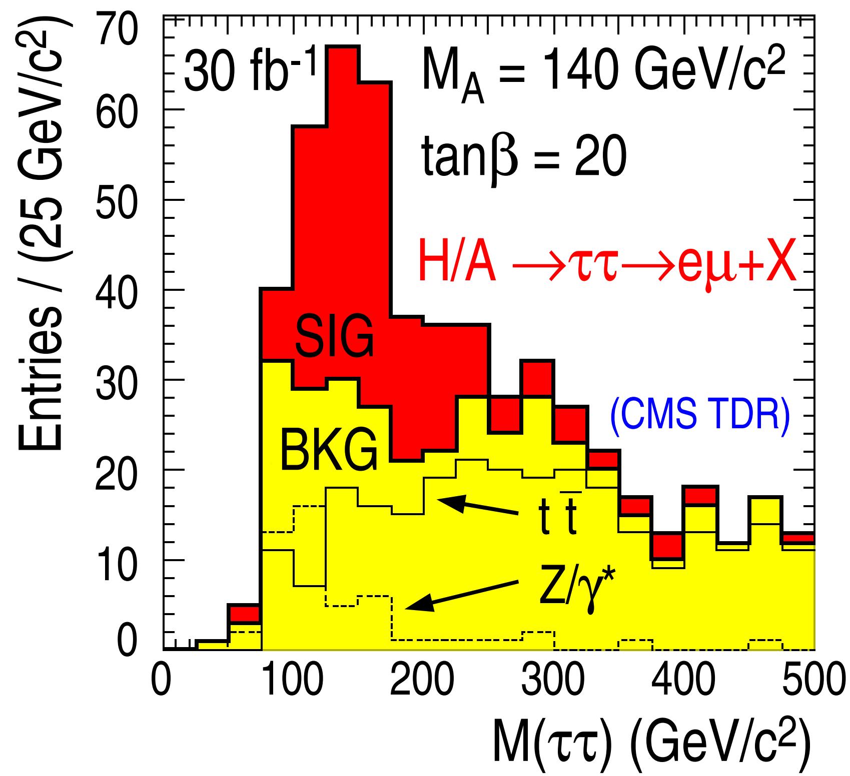
Outlook

- May need to wait >1 decade for TeV-scale lepton collider
- LHC data to provide new discoveries, determine NP mass scale, map its profile
- Hope to probe LHC discoveries with improved precision at future LC

CMS search for $\tau \to \mu\mu\mu$



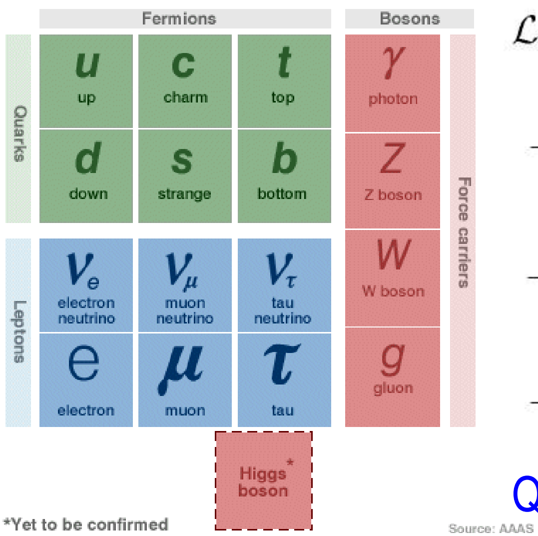
CMS search for H/A



Additional Slides

The Current State of Particle Physics

The **S**tandard **M**odel of Particle Physics:
quantum gauge theory describing the fundamental particles & forces



$$\mathcal{L}_{\rm SM} = i\bar{e}^i_{\rm L}\not{\partial}e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\not{\partial}\nu^i_{\rm L} + i\bar{e}^i_{\rm R}\not{\partial}e^i_{\rm R} + i\bar{u}^i_{\rm L}\not{\partial}u^i_{\rm L} + i\bar{d}^i_{\rm L}\not{\partial}d^i_{\rm L} + i\bar{u}^i_{\rm R}\not{\partial}u^i_{\rm R} + i\bar{d}^i_{\rm R}\not{\partial}d^i_{\rm R}$$ ← kinetic terms

$$-v\left(\lambda^i_e\bar{e}^i_{\rm L}e^i_{\rm R} + \lambda^i_u\bar{u}^i_{\rm L}u^i_{\rm R} + \lambda^i_d\bar{d}^i_{\rm L}d^i_{\rm R} + {\rm h.c.}\right) - M^2_W W^+_\mu W^{-\mu} - \frac{M^2_W}{2\cos^2\theta_W}Z_\mu Z^\mu$$ ← mass terms

$$-\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA}$$ ← field strength terms

$$-g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W+} + W^-_\mu J^\mu_{W-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A$$ ← gauge coupling terms

QCD coupling — Weak coupling — EM coupling

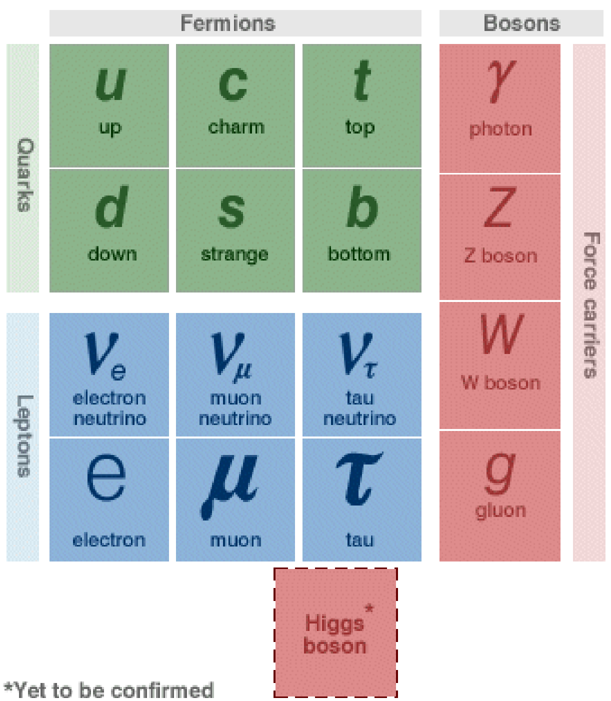
CKM Matrix induces quark flavor mixing

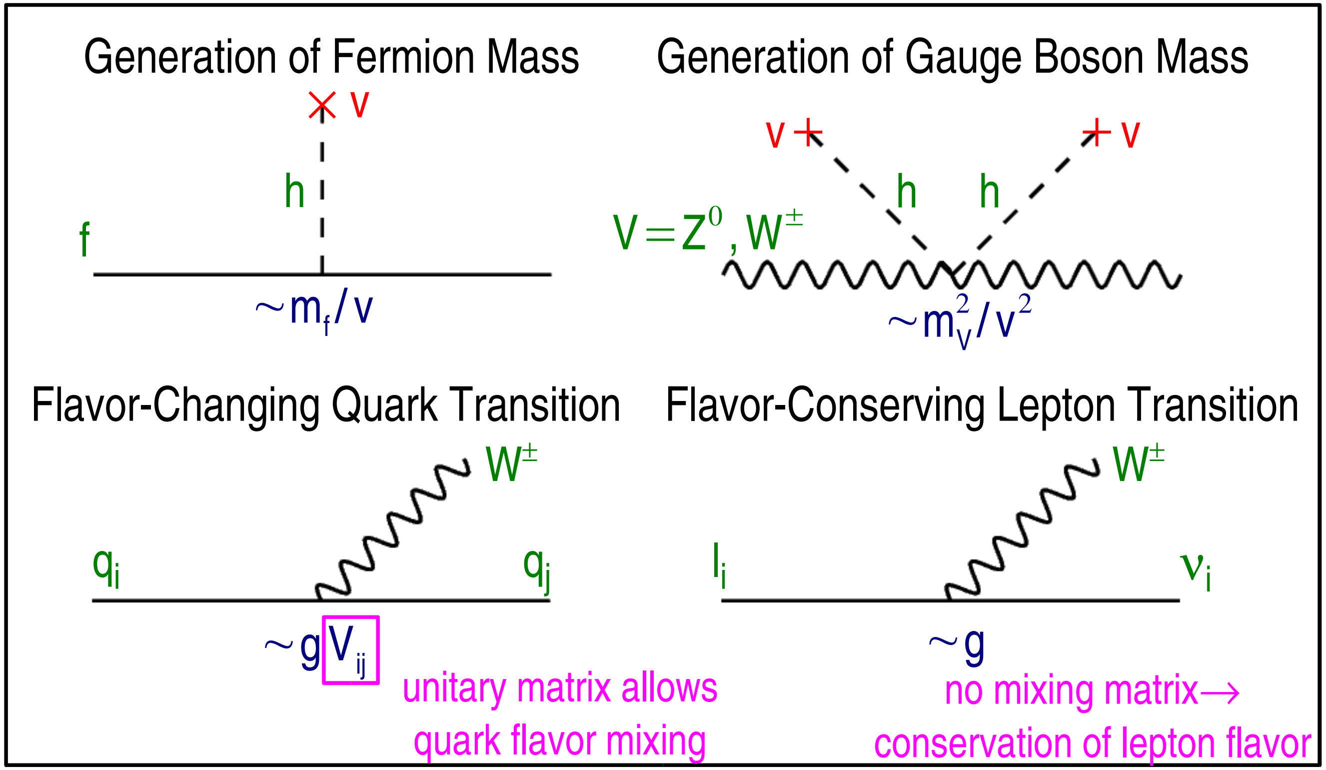
$$J^\mu_{W+} = \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right)$$

- The **SM** has been extremely successful up to highest energies probed by experiment
- But we expect new physics to occur at the TeV scale → **B**eyond **S**tandard **M**odel
- **SU**per**SY**mmetry: solves many problems inherent to **SM**, provides DM candidate

The Current State of Particle Physics

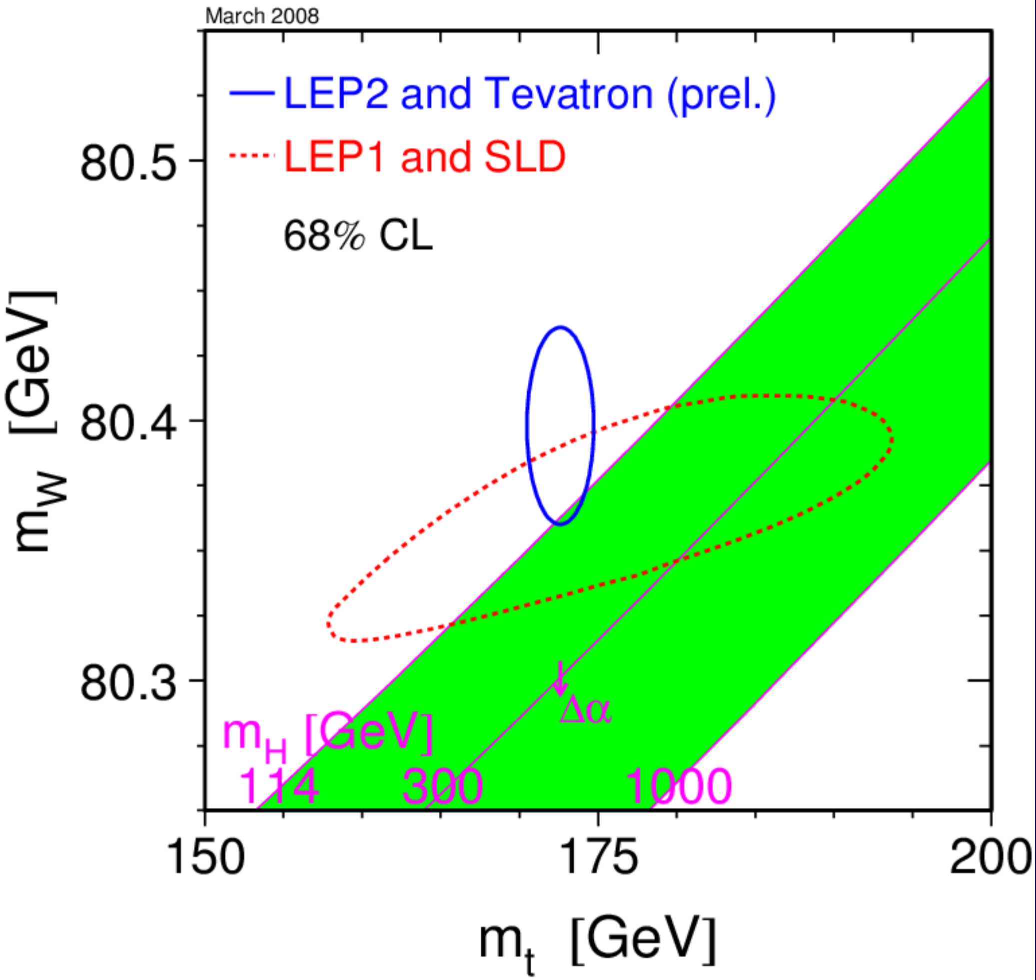
The **Standard Model** of Particle Physics:
quantum gauge theory describing the fundamental particles & forces

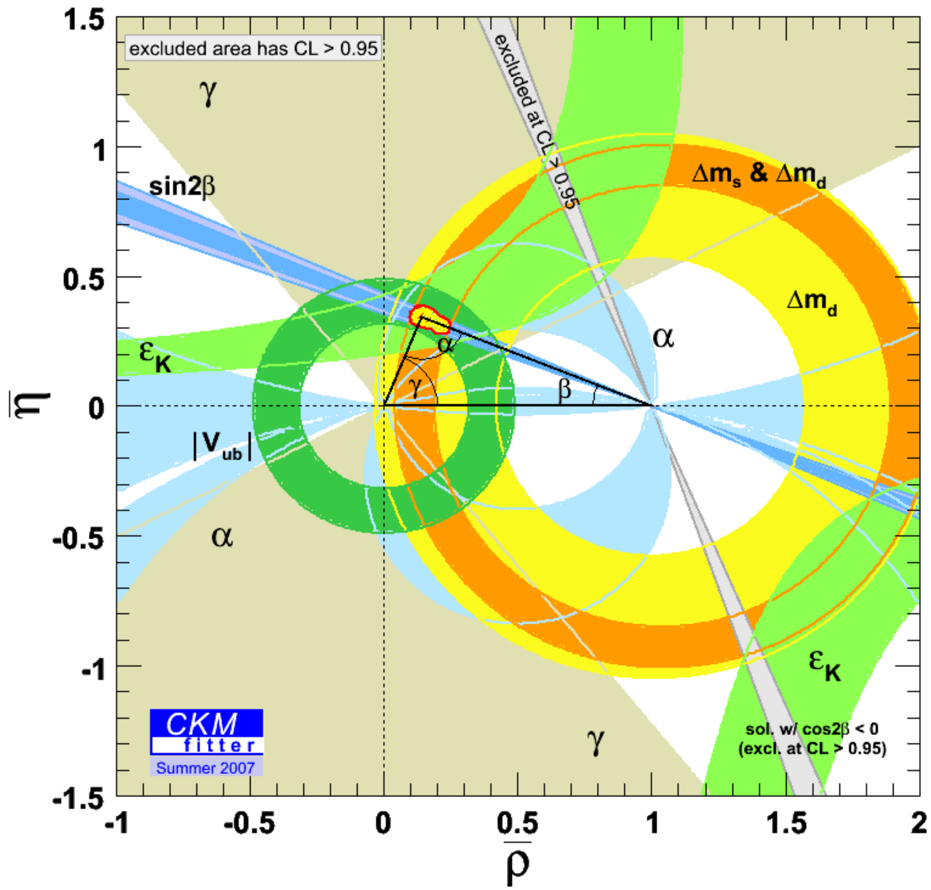




- The **SM** has been extremely successful up to highest energies probed by experiment, but we expect new physics to occur at the TeV scale → **B**eyond **S**tandard **M**odel
- **SU**per**SY**mmetry: solves many problems intrinsic to **SM**, may explain origin of dark matter

Successes of the SM



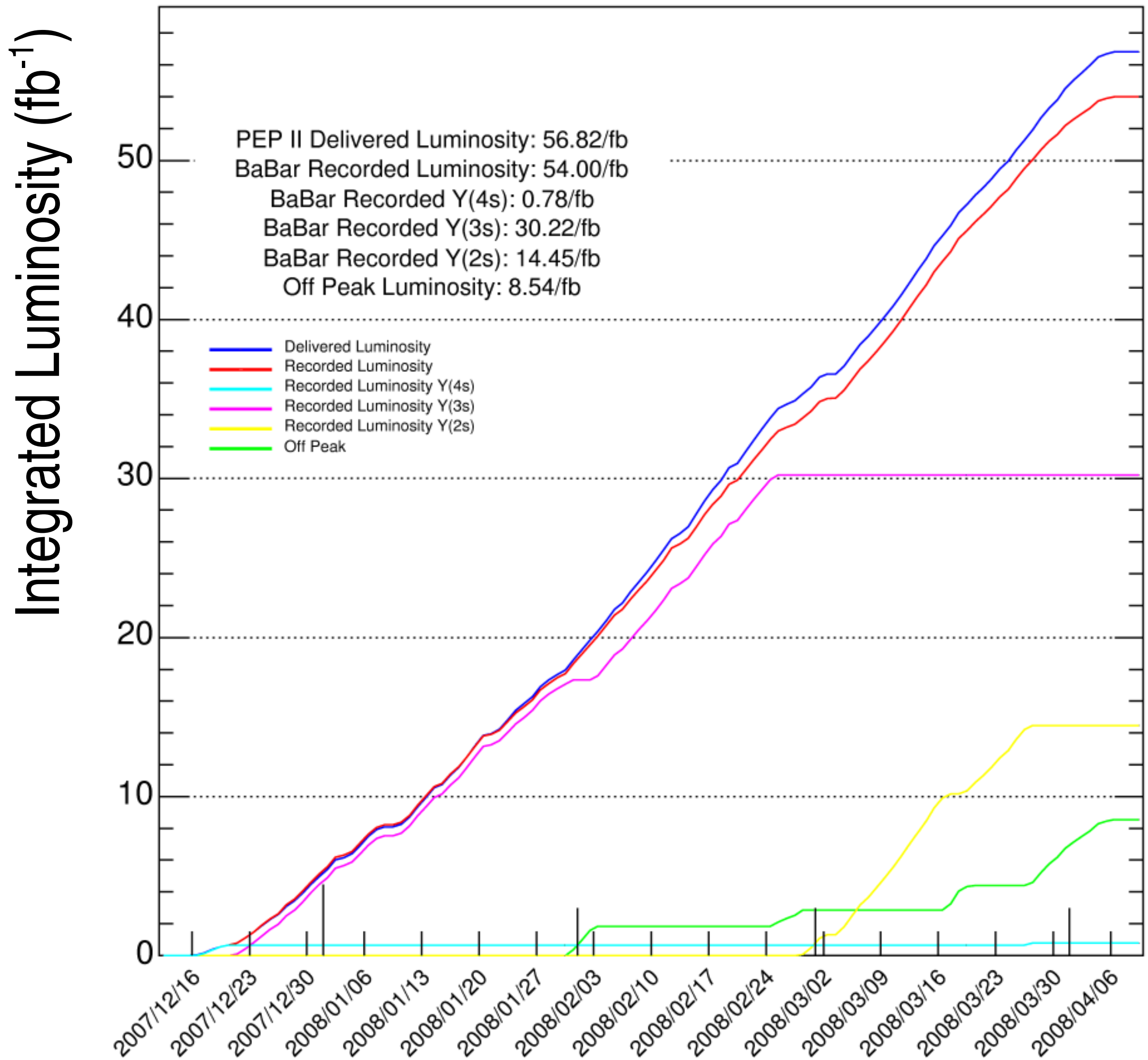


LEP1/SLD indirect m_t prediction agrees with direct measurement from LEP2/Tevatron. Excellent fit to SM with $M_{HIGGS} \lesssim 200$ GeV

All observed CP-violating phenomena (Belle/BaBar/Tevatron) consistent with originating from unitary V_{CKM}

Additional BaBar Slides

BaBar Data-Taking at End of PEP-II Operations

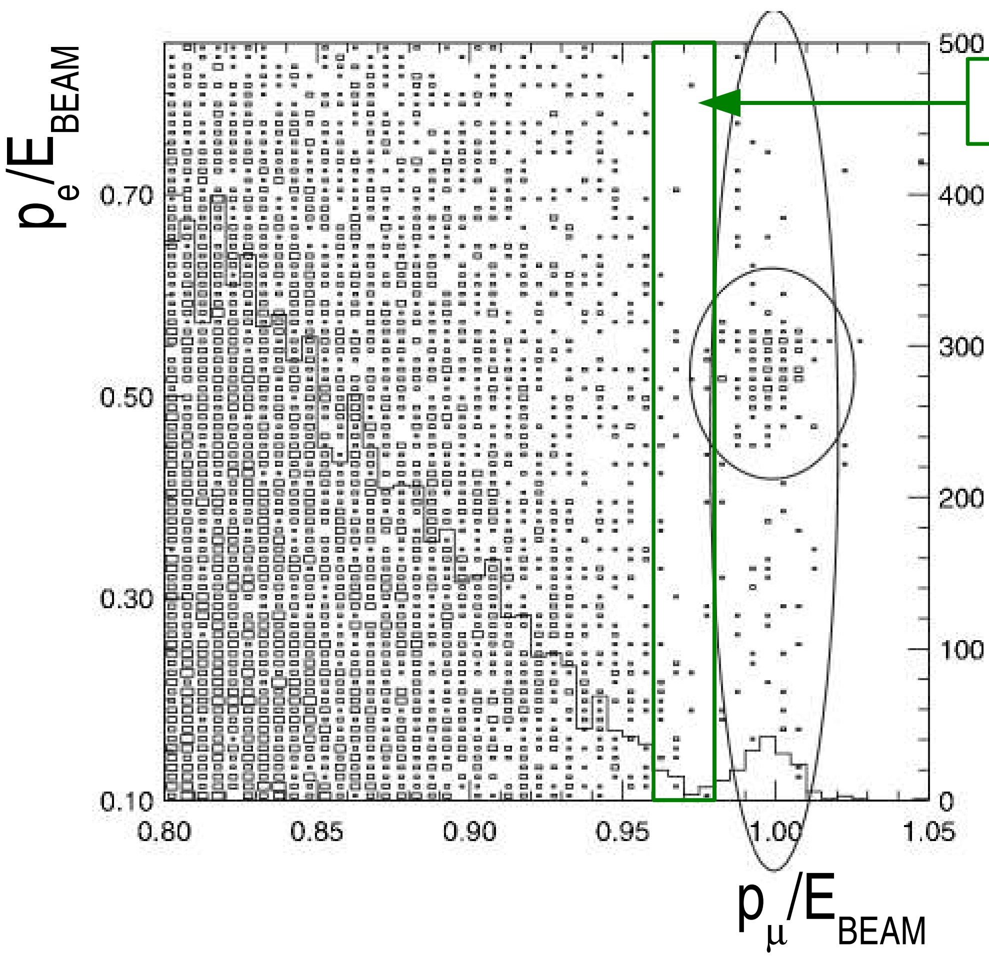


121×10^{6} $\Upsilon(3S)$ decays collected and analyzed

120×10^{6} $\Upsilon(2S)$ decays (analysis to be extended to include $\Upsilon(2S)$ data)

CLEO Upper Limit on $\Upsilon(nS)\to\mu\tau$

Require $\tau\to\mu\nu\nu$ decay



Resonance	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
$N(\Upsilon)$ (10^6)	20	10	5
$BF(\Upsilon\to\mu\tau)$ (10^{-6})	**<6.2**	**<25**	**<22**

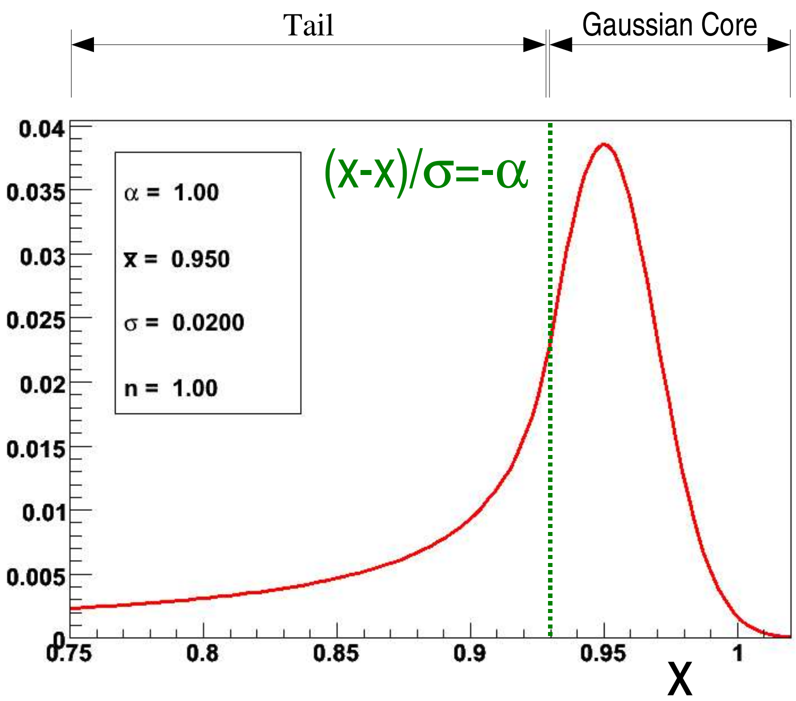
- Anticipate ~5× better sensitivity at BaBar
  - Larger dataset
  - Advanced Particle ID
  - Sensitivity to $\Upsilon\to e\tau$, hadronic τ decay modes

The Crystal Ball and Argus Functions

Crystal Ball Function

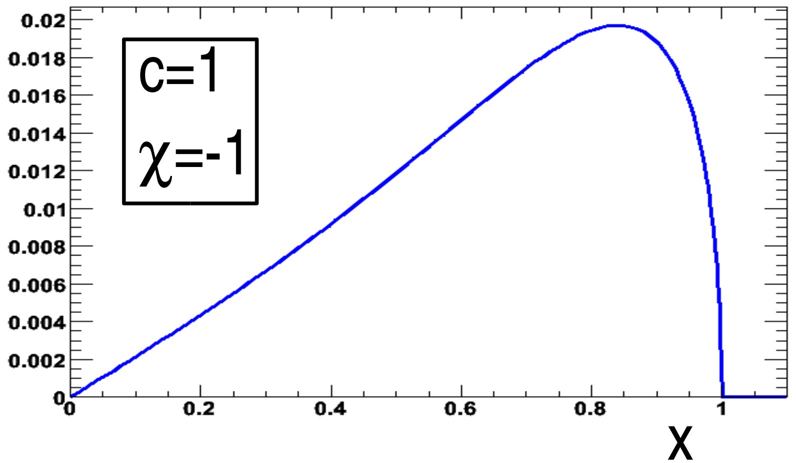
$$CBF(x;\bar{x},\alpha,\sigma,n) = \begin{cases} e^{-(x-\bar{x})^2/2\sigma^2} & (x-\bar{x})/\sigma > -\alpha \\ A\left(B-\frac{x-\bar{x}}{\sigma}\right)^{-n} & (x-\bar{x})/\sigma \le -\alpha \end{cases}$$

$$A=\left(\frac{n}{|\alpha|}\right)^{n} e^{-|\alpha^2|/2},\quad B=\frac{n}{|\alpha|}-|\alpha|$$



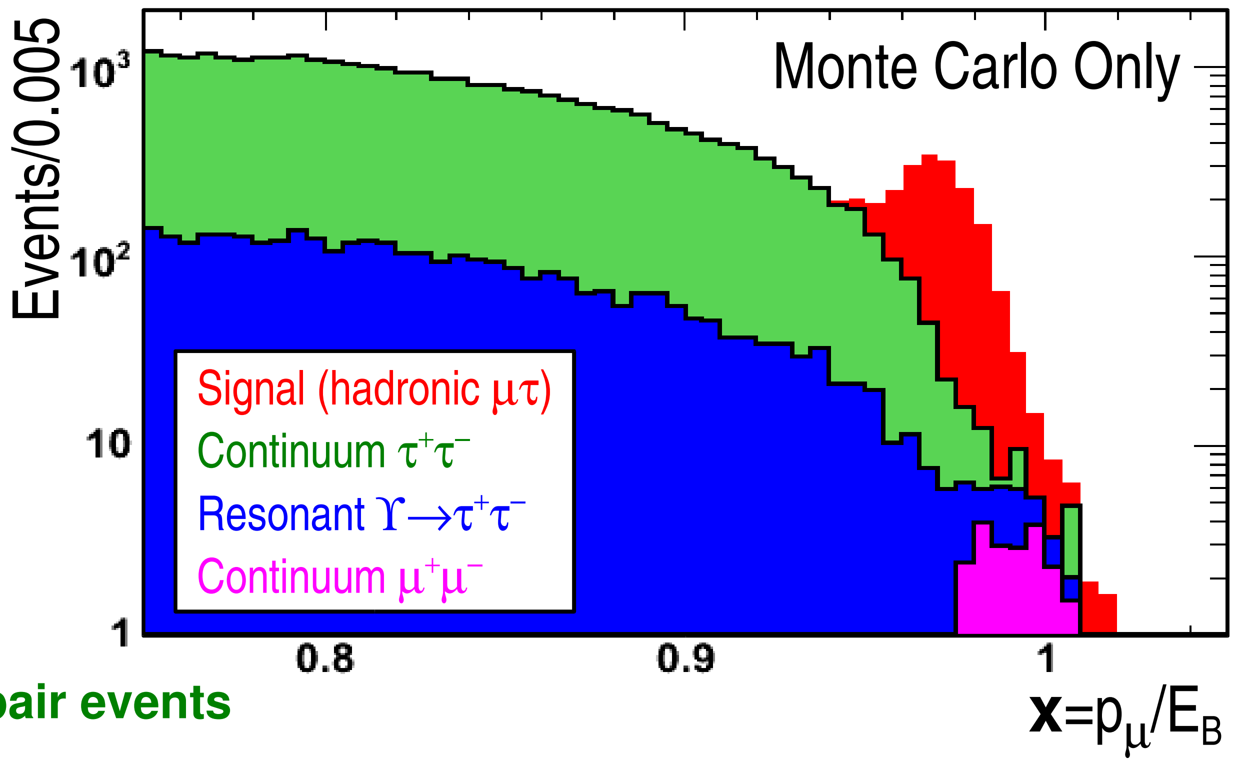
Argus Function

$$AF(x;c,\chi)=x\sqrt{1-(x/c)^2}\,e^{-\chi(1-(x/c)^2)}$$



Signal vs. Backgrounds

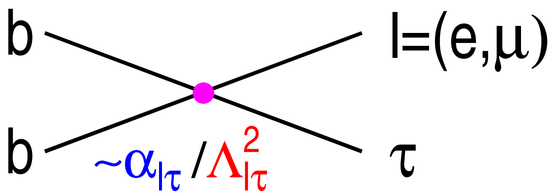
Primary discriminant variable **x**:
x=p_e/E_B for $\Upsilon(3S)\to e\tau$ channels
x=p_μ/E_B for $\Upsilon(3S)\to \mu\tau$ channels



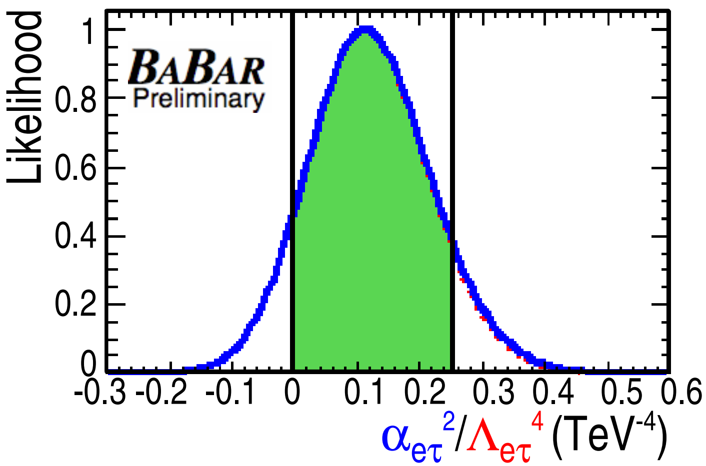
- **Signal $\Upsilon(3S)\to e\tau/\mu\tau$ Production**
  - x distribution peaked at 0.97
- **Main irreducible background: τ–pair events**
  - x distribution follows smooth Michel spectrum truncating at x≈0.97
- **Reducible backgrounds: bhabha events (eτ channels), μ-pair events (μτ channels)**
  - particle mis-ID, μ decay in flight, electron generated in material interaction
  - x distribution has peaking component at x≈1
- **Strategy: unbinned, extended maximum likelihood fit to x distribution**

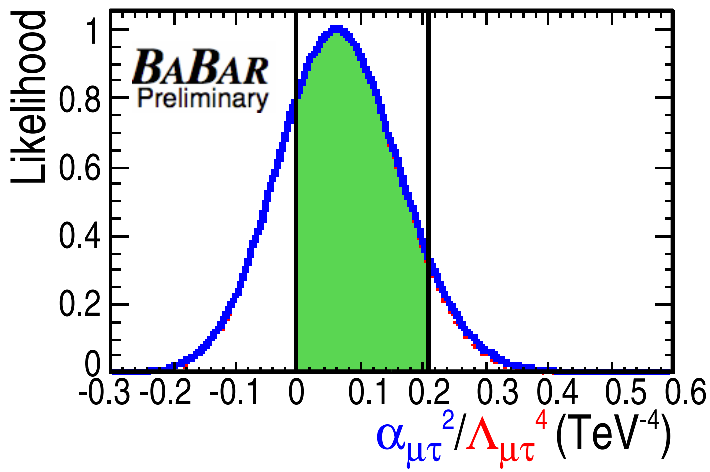
BSM Limits from Effective Field Theory

CLFV Υ decays $\rightarrow$ 4-fermion contact interaction with NP coupling constant and mass scale



$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\rightarrow l\tau)}{BF(\Upsilon(3S)\rightarrow ll)} \frac{2 q_b^2 \alpha^2}{(M_{\Upsilon(3S)})^4} \quad l=(e,\mu)^*$$





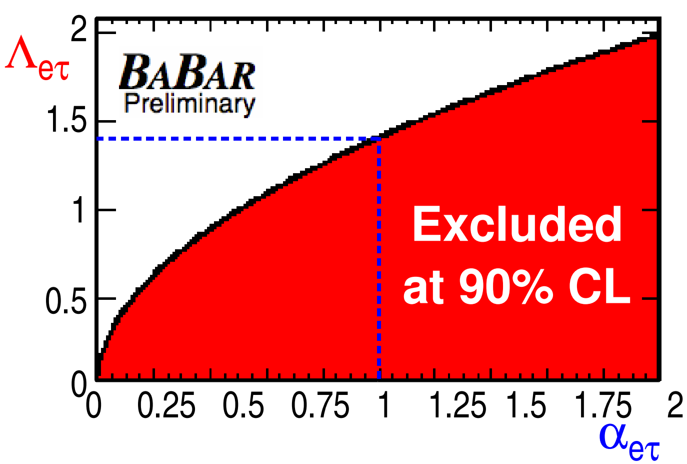
q_b = b quark charge

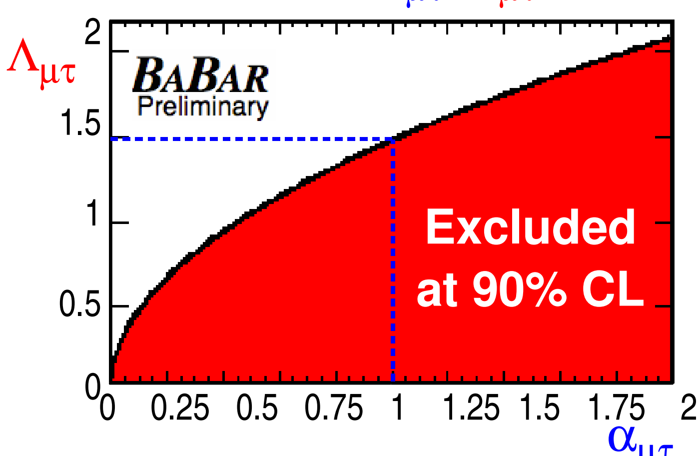
α = fine structure constant

assumes vector coupling

Silagadze Phys. Scripta 64.128

Black et al. PRD 66.053002





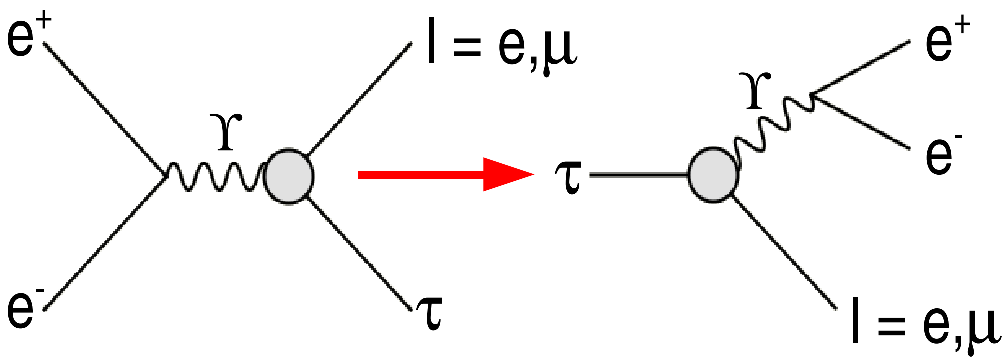
Assume strong coupling $\alpha_{e\tau} = \alpha_{\mu\tau} = 1$:

$\Lambda_{e\tau} > 1.4$ TeV

$\Lambda_{\mu\tau} > 1.5$ TeV

Theoretical Limits on CLFV
Υ Branching Fractions

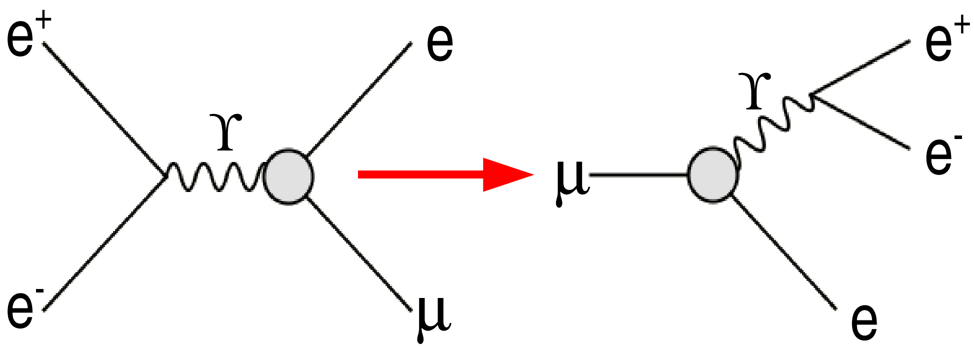
$\Upsilon \to l\tau$ related to $\tau \to lll$ via re-ordering of input/output lines



$$BF(\Upsilon \to l\tau) \le \frac{BF(\tau \to lll)}{BF(\tau \to l\nu\nu)} \frac{\Gamma(W \to l\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \to l^+l^-)} (M_\Upsilon / M_W)^6$$

$BF(\tau \to lll) < 4\text{-}8 \times 10^{-8} \to$ **$BF(\Upsilon(3S) \to l\tau) < 3\text{-}6 \times 10^{-3}$**

$\Upsilon \to e\mu$ related to $\mu \to eee$ via re-ordering of input/output lines



$$BF(\Upsilon \to e\mu) \le BF(\mu \to eee) \frac{\Gamma(W \to l\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \to l^+l^-)} (M_\Upsilon / M_W)^6$$

$BF(\mu \to eee) < 10^{-12} \to$ **$BF(\Upsilon(3S) \to e\mu) < 10^{-8}$**

Nussinov et al. hep-ph/0004153

Nussinov,Peccei,Zhang

- Assume coupling of Υ to eμ looks like: $L_{eff}=g_{\Upsilon e\mu}\bar{\mu}\gamma_{\alpha}e\Upsilon^{\alpha}+h.c.$
- Through Fig 1. this coupling contributes to A($\mu\rightarrow$3e):

$$A(\mu\rightarrow e)=(\bar{u}_{\mu}(p)\gamma^{\alpha}u_e(k_3))(\bar{v}_e(k_1)\gamma_{\alpha}u_e(k_2))\frac{g_{\Upsilon e\mu}g_{\Upsilon ee}}{M_{\Upsilon}^2-s}$$

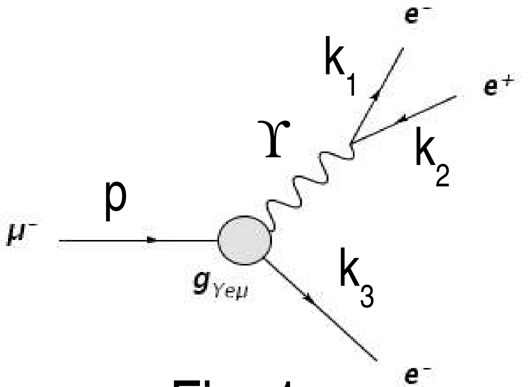


Fig. 1

- Compare $\mu\rightarrow$3e to $\mu\rightarrow$3e$\nu\nu$ (almost identical kinematics)

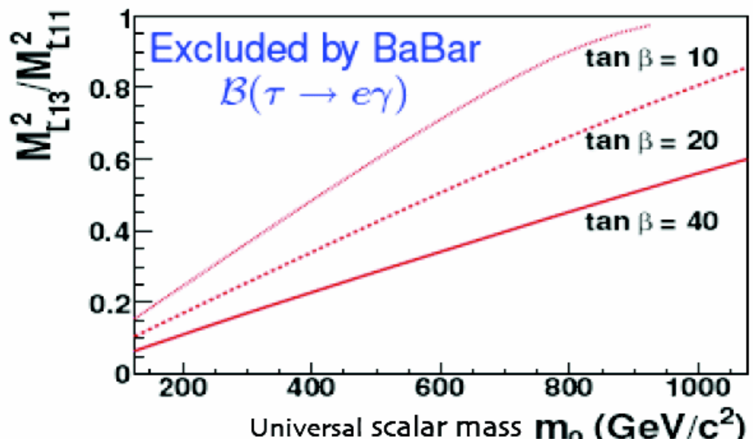
$$\frac{\Gamma(\mu\rightarrow 3e)_{\Upsilon exch}}{\Gamma(\mu\rightarrow e\nu\nu)}\approx\frac{g_{\Upsilon e\mu}^2 g_{\Upsilon ee}^2}{M_{\Upsilon}^4}\frac{M_W^4}{g_W^4}$$

- Make substitutions: $\Gamma(\Upsilon\rightarrow ee)\sim g_{\Upsilon ee}^2 M_{\Upsilon},\Gamma(\Upsilon\rightarrow e\mu)\sim g_{\Upsilon e\mu}^2 M_{\Upsilon},\Gamma(W\rightarrow e\nu)\sim g_W^2 M_W$
- To give:

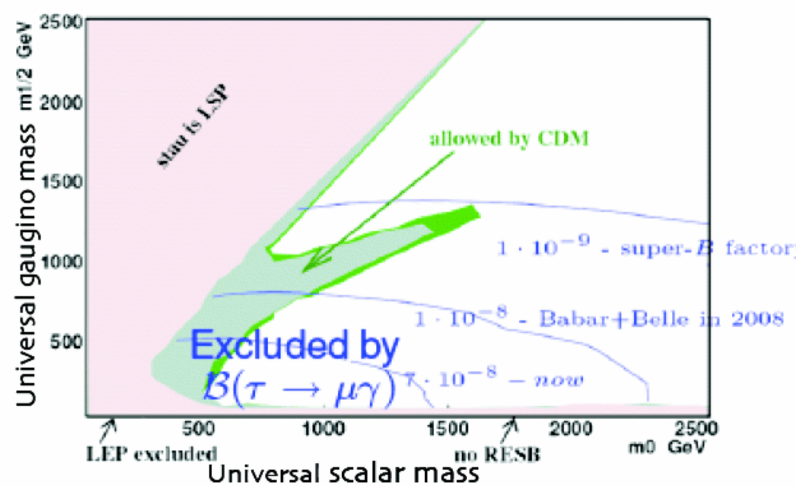
$$BR(\Upsilon\rightarrow e\mu)=BR(\mu\rightarrow eee)\frac{\Gamma(W\rightarrow e\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon_{ee})}(M_{\Upsilon}/M_W)^6$$

Slide from S. Banerjee BNL Seminar 2008

- mSUGRA mixing at GUT scale: $\mathcal{L} = -M^2_{\tilde{L}}\tilde{L}^*\tilde{L} - M^2_{\tilde{E}}\tilde{E}^*\tilde{E}$
  - Model-independent calculation (A.Brignole, A.Rossi, NPB701(2004)3)
  - $m_{GUT} = 5 \cdot 10^{15}$ GeV, $\mu > 0, A_0 = 0$



- mSUGRA + Seesaw: ν-mixing induces LFV at EW scale via RGE
  - RGE using SPheno (W. Porod, CPC153(2003)275)
  - Cold Dark Matter: WMAP Data Simulation with micrOMEGAs (CPC149(2002)103)
  - $m_{\nu_R} = 5 \times 10^{14}$ GeV, $\tan\beta = 55$, $\mu > 0, A_0 = 0, m_0, m_{1/2}$, $M^2_{\tilde{L}}, M^2_{\tilde{E}}$: Diagonal



Limits from LFV μ Decays

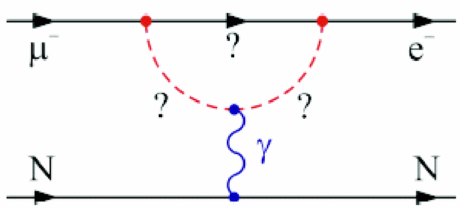
Slide from Yury Kolomensky 290E Seminar 2009

$\mu^- N \to e^- N'$ and $\mu^+ \to e^+\gamma$ Complementary

Model independent CLFV Lagrangian: (A. de Gouvea)

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

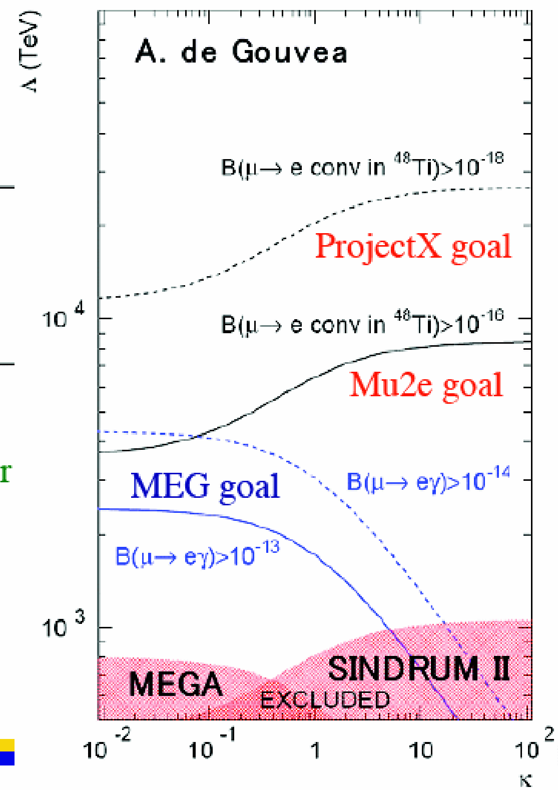
assumes unit coupling

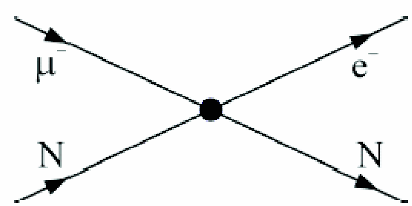


$\kappa \ll 1$

magnetic moment type operator

$\mu \to e\gamma$ rate ~300x $\mu N \to eN'$ rate





$\kappa \gg 1$

four-fermion interaction

$\mu N \to eN'$ greatly enhanced over $\mu \to e\gamma$ rate

01/28/2009

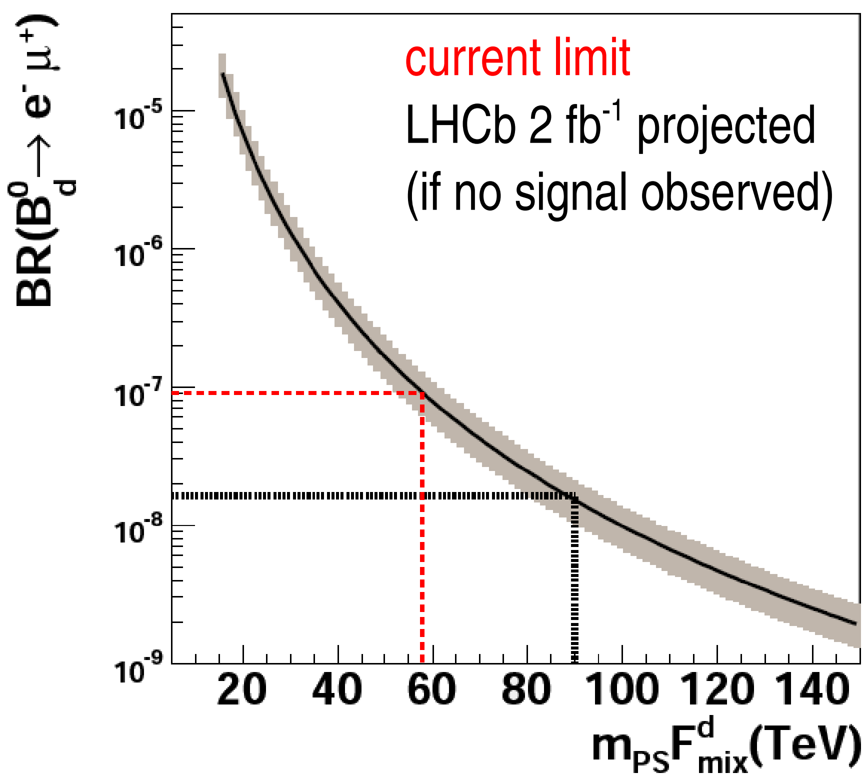
YGK: LFV

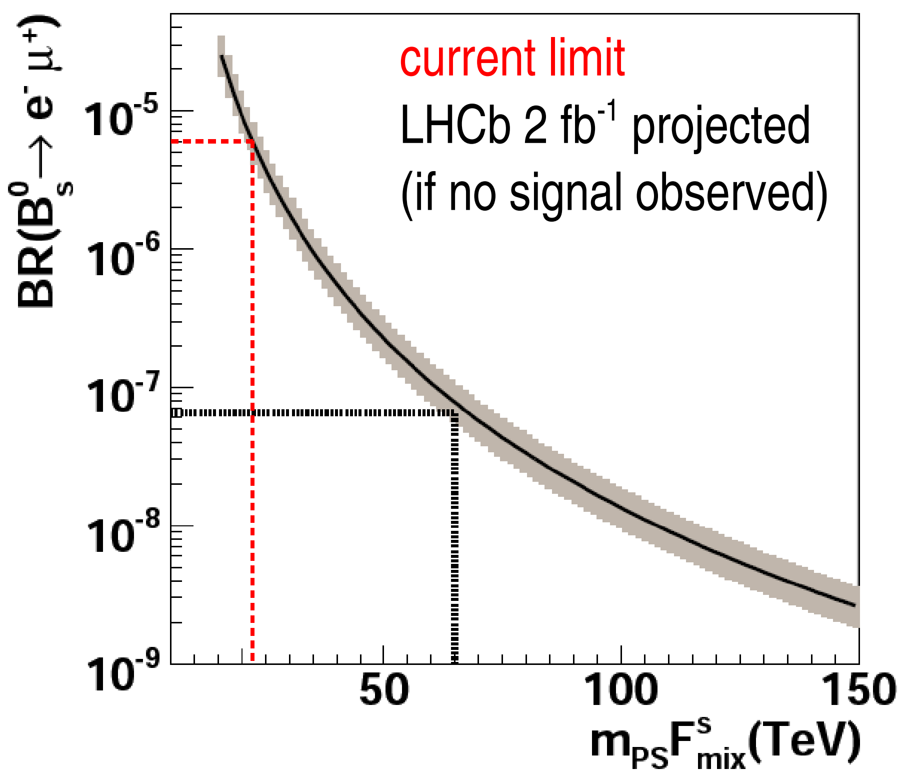
Limits from $B^0_{d,s} \to e\mu$ on Pati-Salam Leptoquark Model

arXiv:0801.1826

PS leptoquark mass — PS generation mixing parameter >1

- $BF(B^0_d \to e\mu) < 9\times10^{-8}$ (Belle) $\to m_{PS} F^d_{mix} > 58$ TeV
- $BF(B^0_s \to e\mu) < 6\times10^{-6}$ (CDF) $\to m_{PS} F^s_{mix} > 21$ TeV





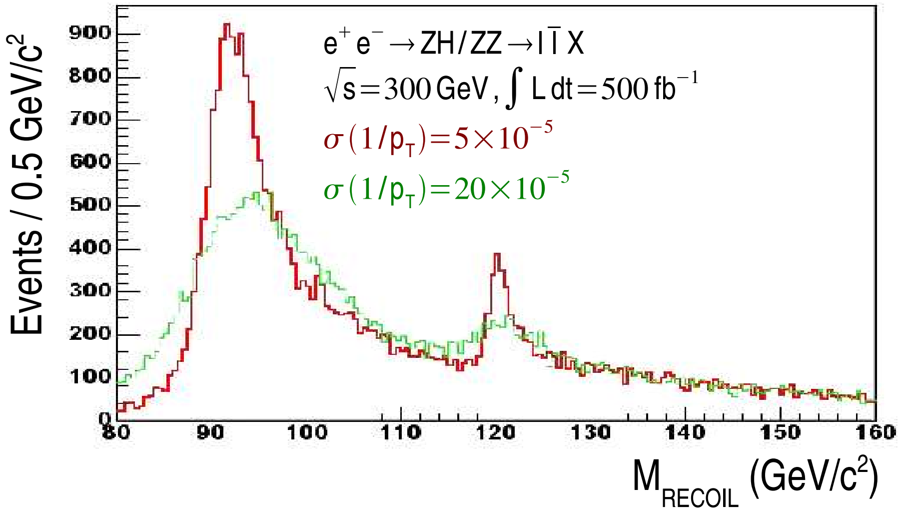
Additional Detector R&D Slides

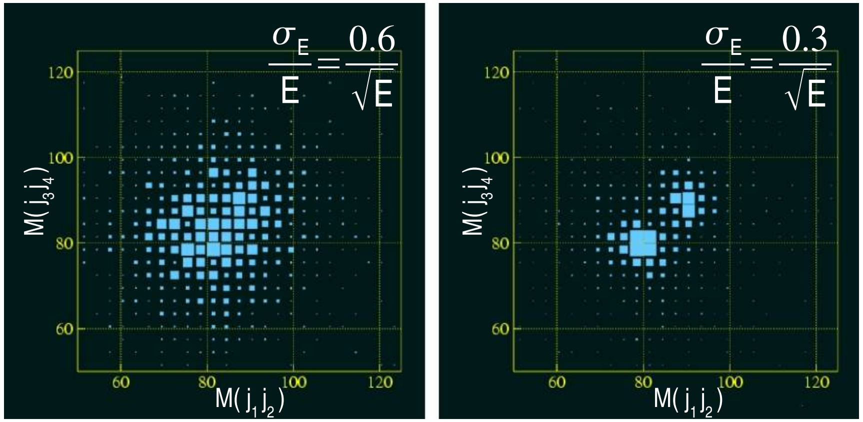
Toward a Future LC Detector

- Un-precedented detector performance required to reach physics goals
- **R**esearch and **D**evelopment effort focus of world-wide study

E, p_T expressed in GeV

Detector/Figure of Merit		DELPHI	ATLAS	ILC target
Vertex Tracker/ Impact Parameter Res	$\sigma_{IP}(\mu m)$	$20 \oplus \frac{65}{p_T \sqrt{\sin\theta}}$	$11 \oplus \frac{70}{p_T \sqrt{\sin\theta}}$	$5 \oplus \frac{10}{p_T \sqrt{\sin\theta}}$
Tracking Detector/ Momentum Resolution	$\sigma(\frac{1}{p})(GeV^{-1})$	1×10^{-3}	5×10^{-4}*	5×10^{-5}
Calorimetry+Particle Flow/ Jet Energy Resolution	$\frac{\sigma_E}{E}$	$\frac{0.9}{\sqrt{E}}$	$\frac{0.5}{\sqrt{E}} \oplus 0.02$	$\frac{0.3}{\sqrt{E}}$





$e^+e^- \to W^+W^-/Z^0Z^0$ Discrimination

Toward a Future LC Detector

- Un-precedented detector performance required to reach physics goals
- Research and Development effort focus of world-wide study

E, p_T expressed in GeV

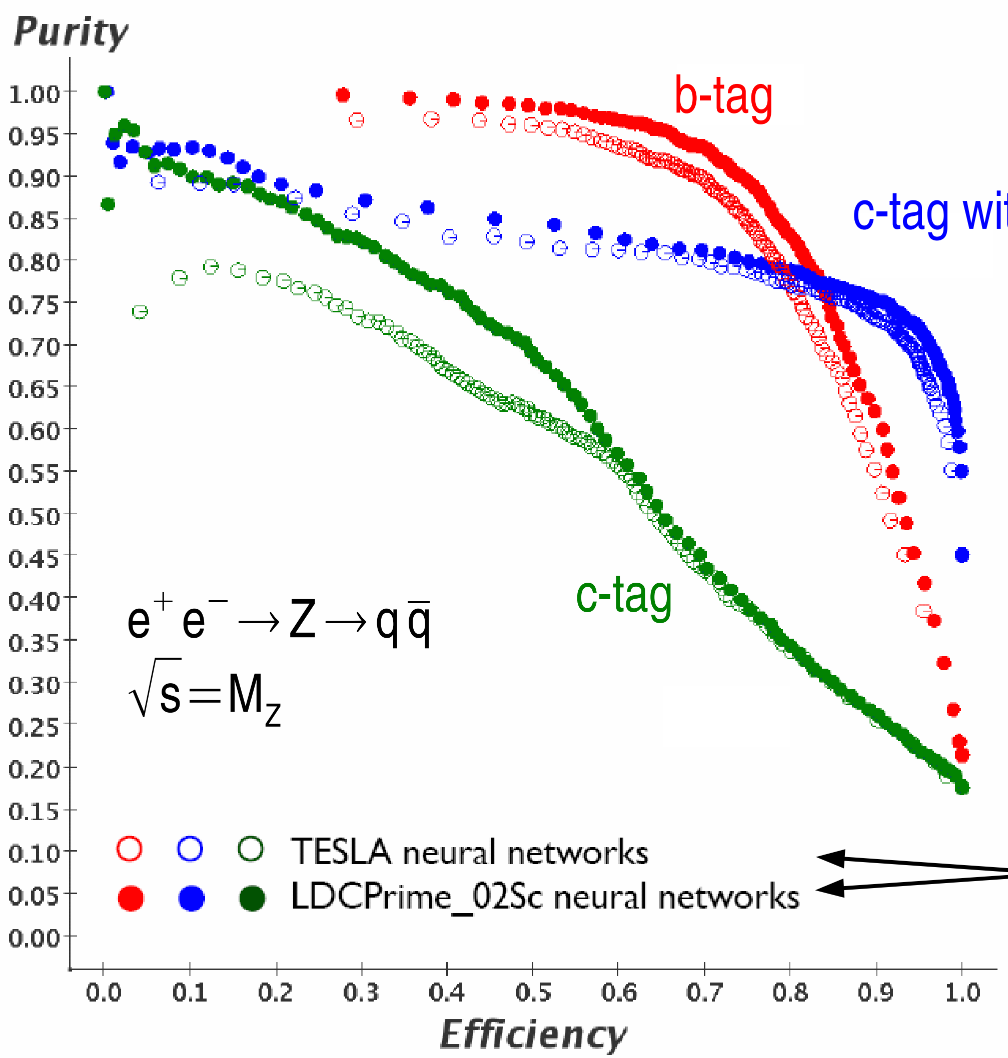
Detector/Figure of Merit		DELPHI	ATLAS	ILC target
Vertex Tracker/ Impact Parameter Res	$\sigma_{IP}(\mu m)$	$20 \oplus \frac{65}{p_T \sqrt{\sin\theta}}$	$11 \oplus \frac{70}{p_T \sqrt{\sin\theta}}$	$5 \oplus \frac{10}{p_T \sqrt{\sin\theta}}$
Tracking Detector/ Momentum Resolution	$\sigma(\frac{1}{p})(GeV^{-1})$	1×10^{-3}	$5\times10^{-4}*$	5×10^{-5}
Calorimetry+Particle Flow/ Jet Energy Resolution	$\frac{\sigma_E}{E}$	$\frac{0.9}{\sqrt{E}}$	$\frac{0.5}{\sqrt{E}} \oplus 0.02$	$\frac{0.3}{\sqrt{E}}$

- Study dependence of c-tagging efficiency on IP resolution →
- Assume Z^0 flavor composition, fix c purity = 0.7
- Total efficiency ~ ε_C^N (N=# tagged jets)

Geometry	σ_{IP} (μm)	ε_C
R1=1.2 cm	$4\oplus7/p_T$	0.49
R1=1.7 cm	$4\oplus10/p_T$	0.46
R1=2.1 cm	$5.5\oplus14/p_T$	0.40
Hybrid Pixel Sensors	$11\oplus15/p_T$	0.29

b/c-Tagging with the LCFIVertex Algorithm

LCFIVertex algorithm: feeds track/vertex info into neural net which discriminates btw b/c/q jets



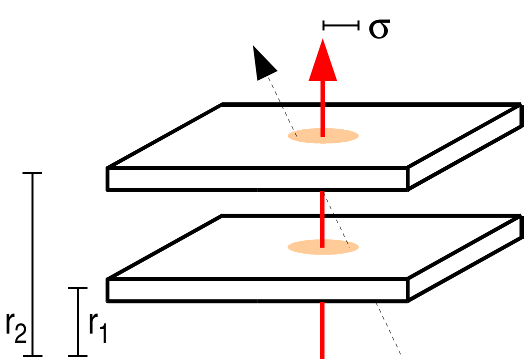
2 ILC detector layouts under consideration

Walsh arXiv:0901.4894

Physics Requirements for VTX

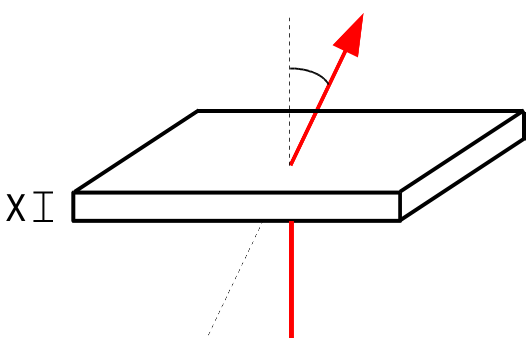
- Impact Parameter Resolution: (**5** $\oplus$ **10** /p $\sin^{3/2}(\theta)$) µm
  - Spatial extrapolation resolution σ < 4 µm →
  - Multiple Scattering: material budget X/X_0 < 0.1% per layer →
- High granularity (high background) →
- Radiation tolerance, fast readout

→ Monolithic Pixel Sensors



$$\sigma_{EE} = \sigma \frac{\sqrt{r_1^2 + r_2^2}}{r_2 - r_1}$$

Extrapolation Error

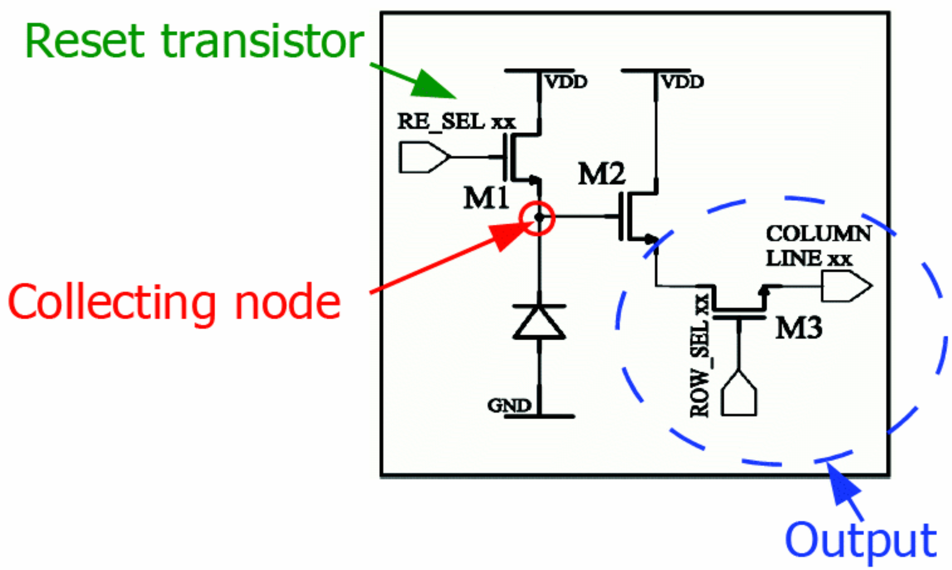


$$\sigma_{MS} = \frac{1}{p_T}\sqrt{\frac{X}{X_0}}$$

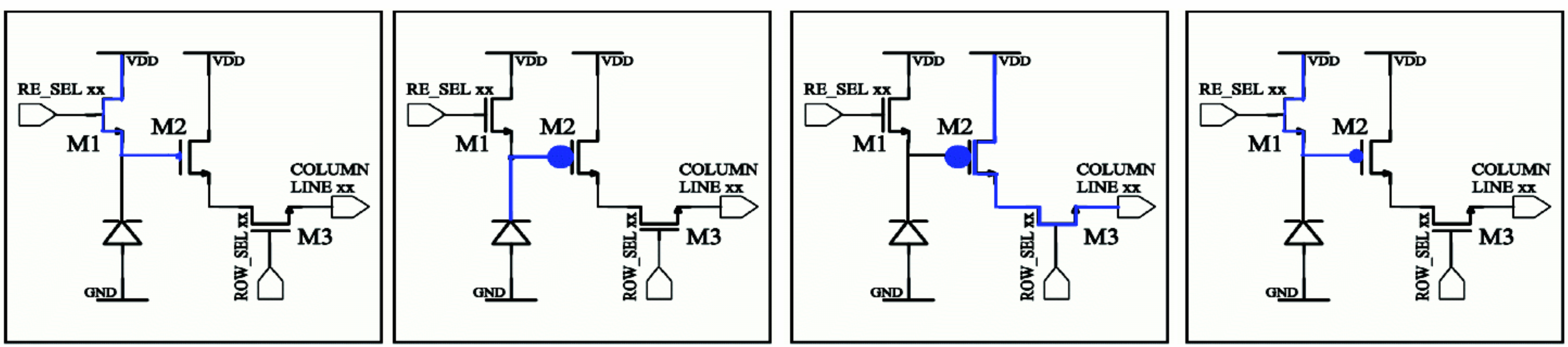
Multiple Scattering

Single Pixel Readout

slide from D. Contarato Warsaw University Presentation 2005



- Classical 3T architecture (3 transistors)
- Other designs possible and also considered
- Single pixel level: reset cycle + integration + readout + reset …

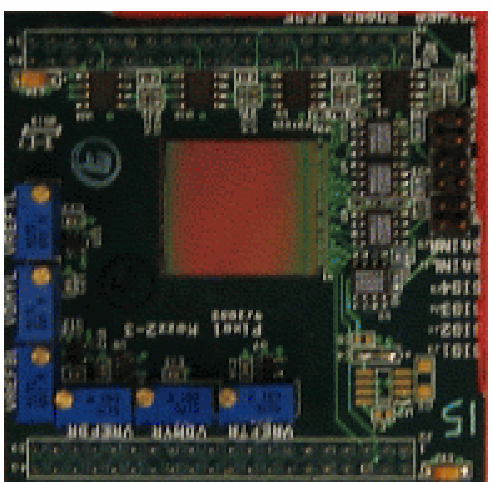


Reset (common row) | **Collection** (int. time=frame rate) | **Output** | **Reset…**

Back-Thinning Procedure

- **Step 1:** Attach chip to PCB with removable WaferGrip adhesive, characterize
- **Step 2:** Remove glue by placing in heated solvent
- **Step 3:** Mechanical grind back-thinning to 50 μm by Aptek Industries
- **Step 4:** Re-attach chip to PCB with permanent glue, re-characterize

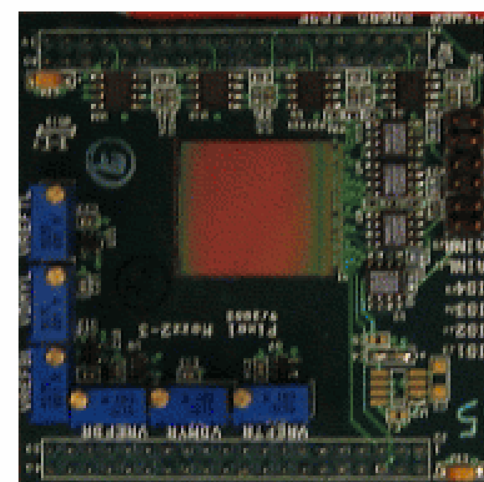
1



2

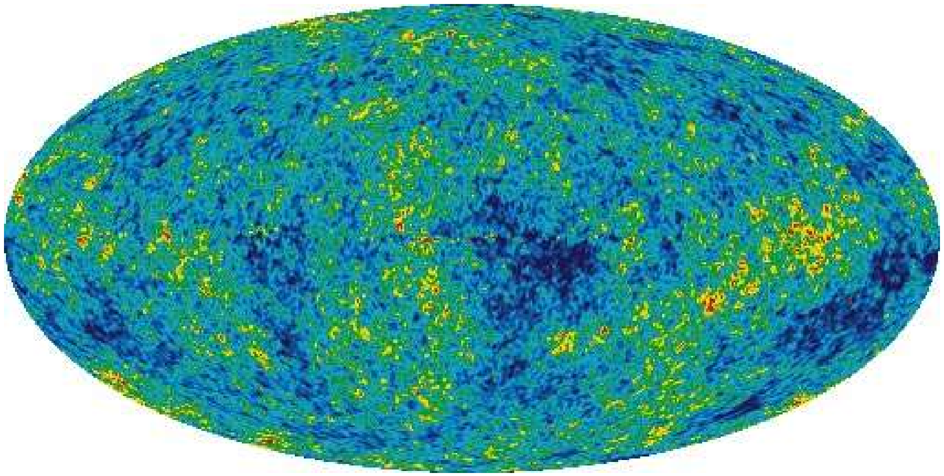
3

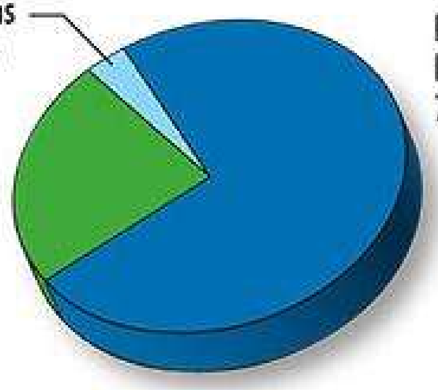
4



Additional DM/SUSY Slides

Wilkinson **M**icrowave **A**nisotropy **P**robe
All-Sky Image of **C**osmic **M**icrowave **B**ackground

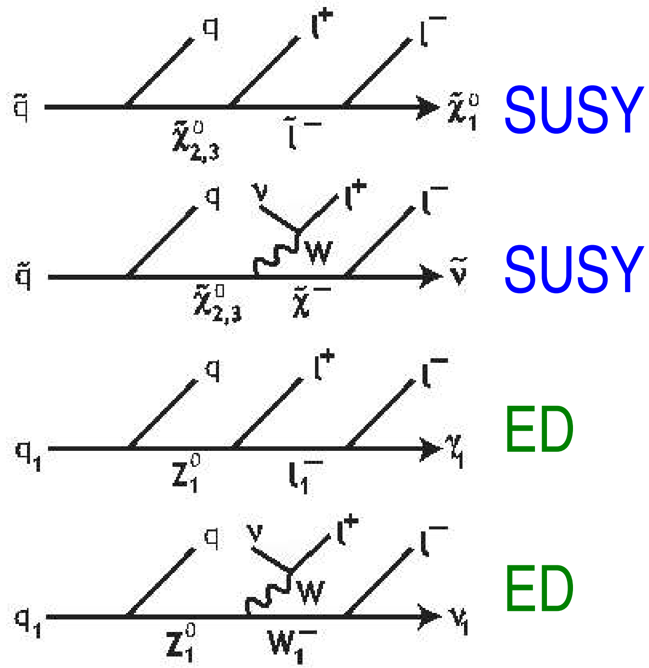


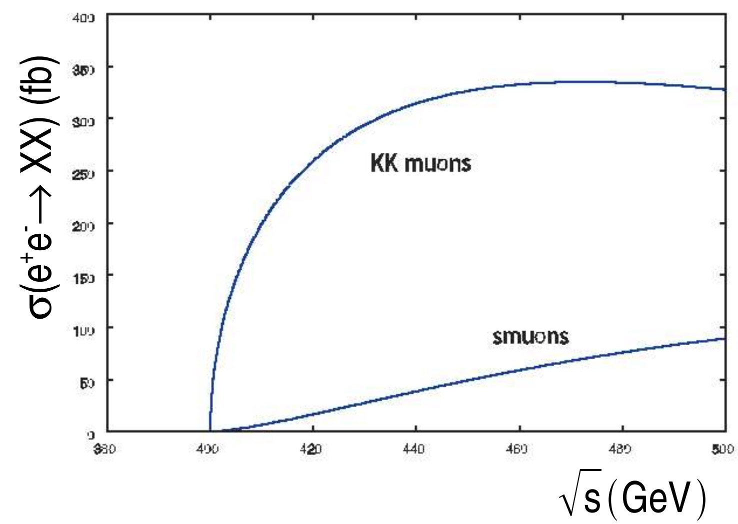


- Compelling body of evidence from wide variety of sources indicates existence of dark matter (**DM**)
- WMAP measurements of CMB: DM relic density $\Omega_{DM}=\rho_{DM}/\rho_{crit} = 0.233 \pm 0.013$
- Experimentally favored explanation: DM is composed of weakly-interacting massive particles (**WIMP's**) with M_{WIMP} = **O(10^2) GeV!** coincidence or indication that DM is composed of SUSY particles?
- To be probed at Large Hadron Collider (**LHC**), future lepton collider such as International Linear Collider (**ILC**)

WIMP Dark Matter at Colliders

- **Detection at LHC:**
  - $\tilde{q}/\tilde{g}$ pair production with cascade to SM particles & WIMP
  - if $M_{\tilde{q}}$ or $M_{\tilde{g}}$<1 TeV, discovery @ $\int Ldt$=100 pb^{-1}~1 month!
  - Difficult/impossible to distinguish between BSM Models
- **Precision probe at future LC:**
  - direct production $e^+e^- \rightarrow XX$
  - spin determined by threshold behavior
  - Precision measurements of masses, couplings
- **Ultimate goal:**
  - comprehensive set of LHC+LC measurements combined with understanding of underlying theory to predict $\Omega_{WIMP}h^2$ and compare with direct detection
  - LC unique in precision measurements needed for $\Omega_{WIMP}h^2$ determination





Full Simulation & Reconstruction

Use software chain to generate, simulate, reconstruct physics processes at future LC

Pythia+ISASUGRA: Event Generation

e^+e^- collider @ 1 TeV, LCC-4 benchmark point

↓ stdhep

GEANT4/Mokka: Detector Simulation

LDC detector concept w/ realistic VTX geometry

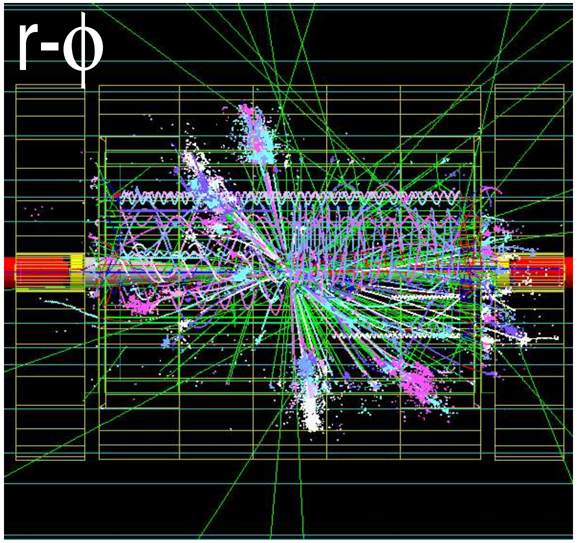
↓ slcio

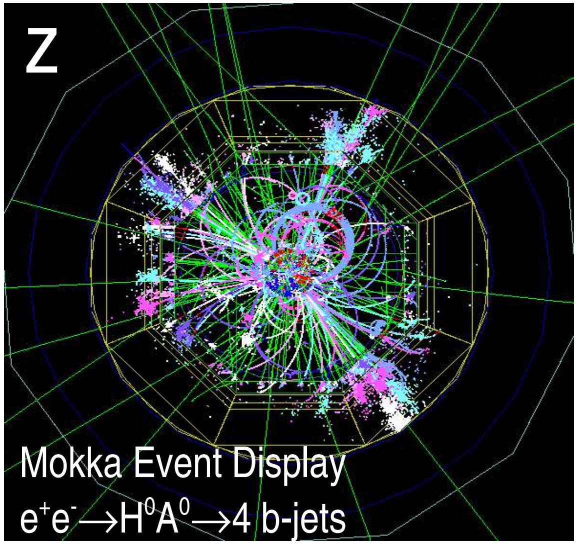
Marlin: Reconstruction

LCIO-based C++ framework: hit digitization, tracking & clustering, particle flow, jet clustering, b-tagging

↓ root ntuple

Root: Data Analysis





The Constrained Kinematic Fit

- Problem: 4-jet final state ($\Delta E/E \approx$ 0.03-0.05, lost/mis-assigned particles, neutrinos)
- Improve jet energy resolution with constrained kinematic fit algorithm
- Implement PUFITC algorithm from DELPHI in dedicated Marlin module:

Adjust jet momenta given by: $\vec{p}_F = e^a \vec{p}_M + b\,\vec{p}_B + c\,\vec{p}_C$

while satisying constraints: $p_X^{TOT} = p_Y^{TOT} = 0,\ E^{TOT} + |p_Z^{TOT}| = \sqrt{s}$

and minimizing χ^2: $\chi^2 = \Sigma_i \frac{(a_i - a_0)}{\sigma_a^2} + \frac{b_i}{\sigma_b^2} + \frac{c_i}{\sigma_c^2}$

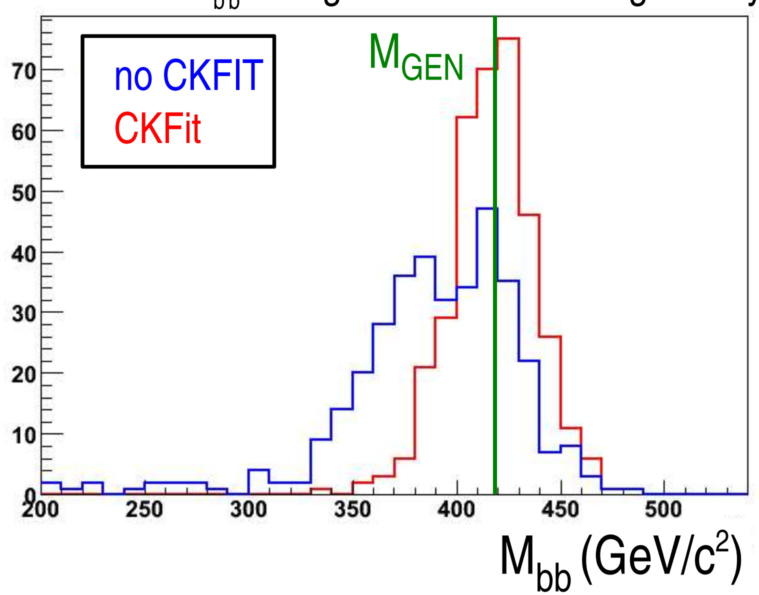
$\vec{p}_F$ = fitted momentum, $\vec{P}_M$ = measured momentum

$\vec{p}_b, \vec{p}_c$ = unit vectors $\perp \vec{p}_M$ and each other

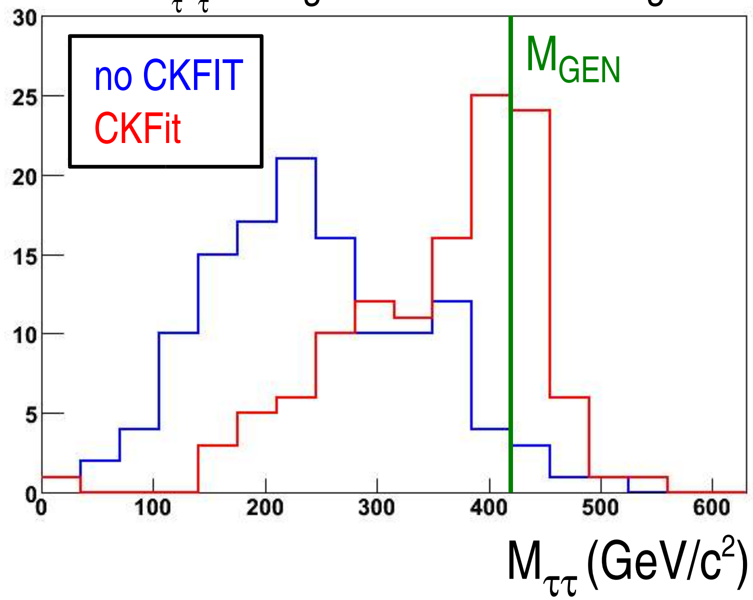
a_0 = expected energy loss, σ_a = energy resolution

σ_b, σ_c = transverse momentum resolution

Measure $M_{b\bar{b}}$ using $H^0 A^0 \to b\bar{b}b\bar{b}$ signal only

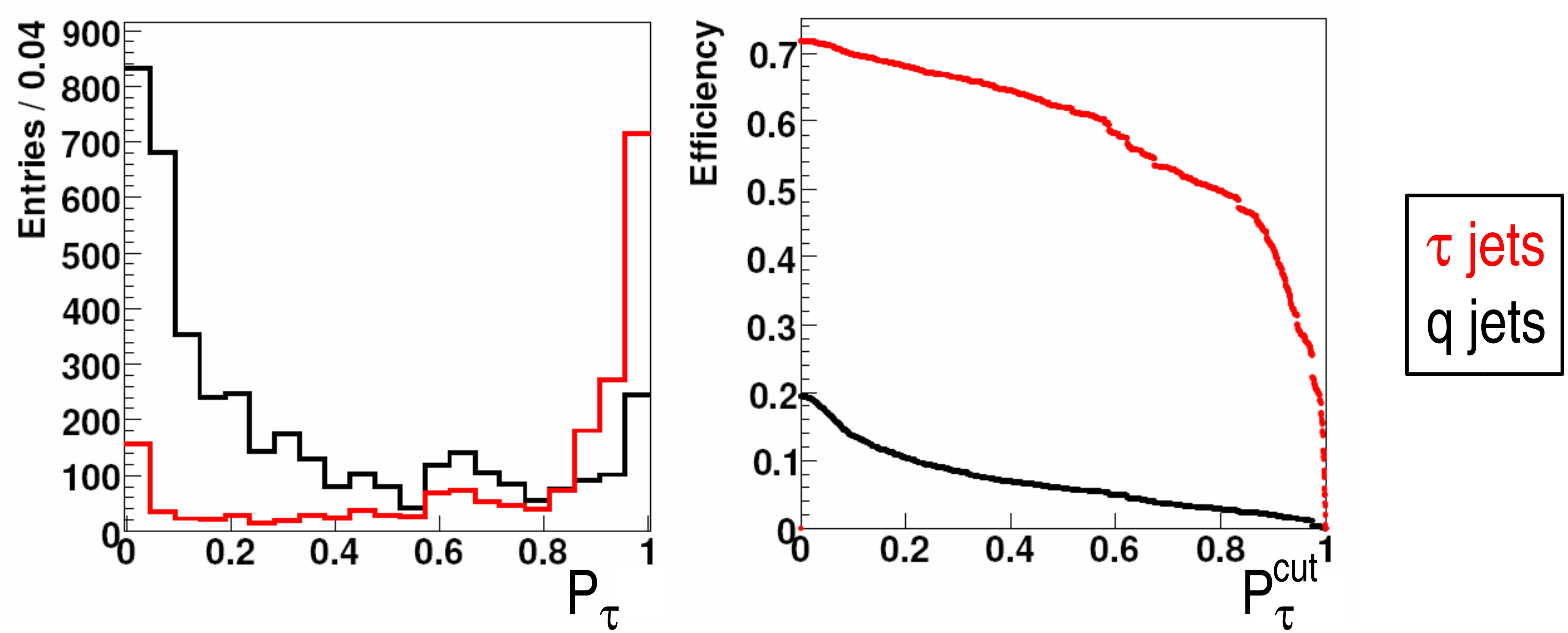


Measure $M_{\tau^+\tau^-}$ using $H^0 A^0 \to b\bar{b}\tau^+\tau^-$ signal only

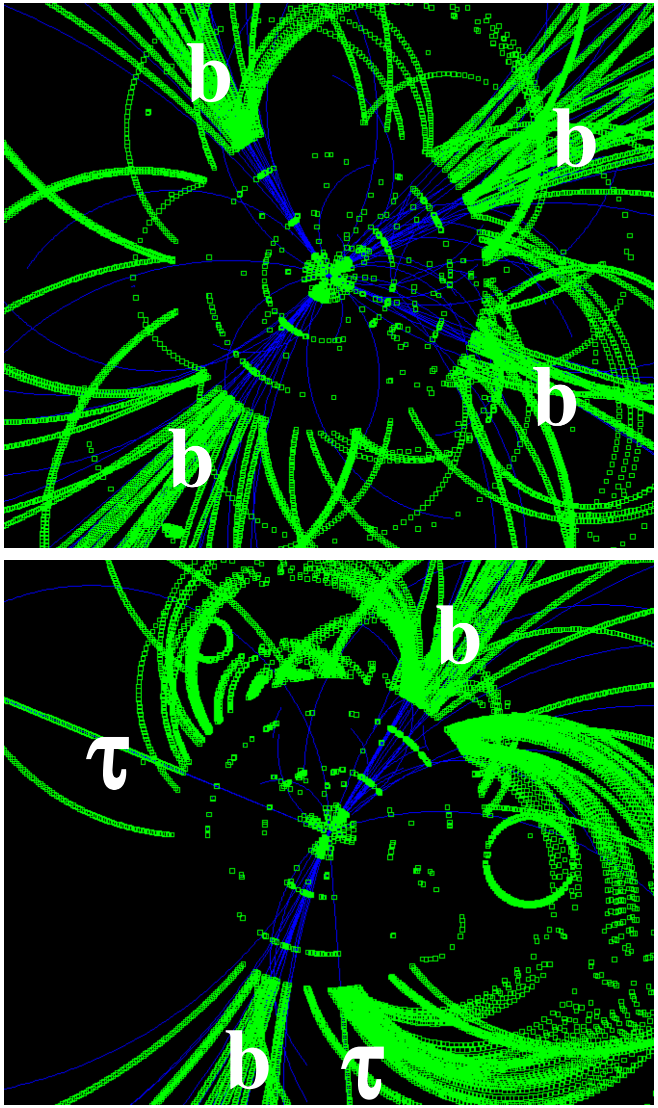


τ-tagging Algorithm (based on CMS algorithm)

- τ, light q jets have similar signatures
- Distinguish between τ/q using discriminant variable P_τ based on 3 variables
  - Secondary vertex mass
  - Impact parameter of track with greatest transverse momentum
  - $P_{ISOL} = \sum_{\Delta R<0.40} E_T - \sum_{\Delta R<0.13} E_T \quad \left(\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \right)$



Measuring BF($H^0/A^0 \to \tau^+\tau^-$)

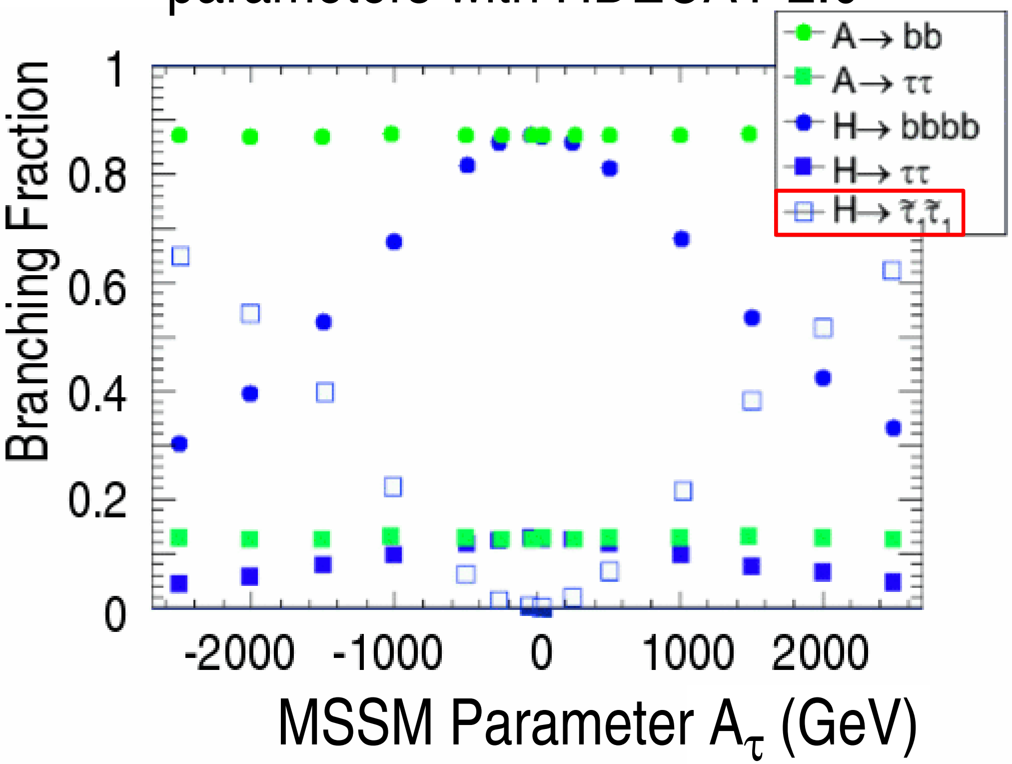


Mokka event display

- Measure BF($H^0/A^0 \to \tau^+\tau^-$) from rate of $H^0A^0 \to b\bar{b}\tau^+\tau^-$ vs $H^0A^0 \to b\bar{b}b\bar{b}$
- 2 b tags with 300 GeV<$(M_{bb})^{CKFit}$<600 GeV + 2 τ tags
- Developed τ tagging algorithm
  - jet mass, leading track IP, $P_{ISOL} \to P_\tau$
- Consider W^+W^-, Z^0Z^0 and $t\bar{t}$ background
- Kinematic/event shape cuts + missing energy
- 88 signal events, 76 background events: estimated BF uncertainty $\left(Sig/\sqrt{Sig+Bkg}\right)^{-1}$ is 15%

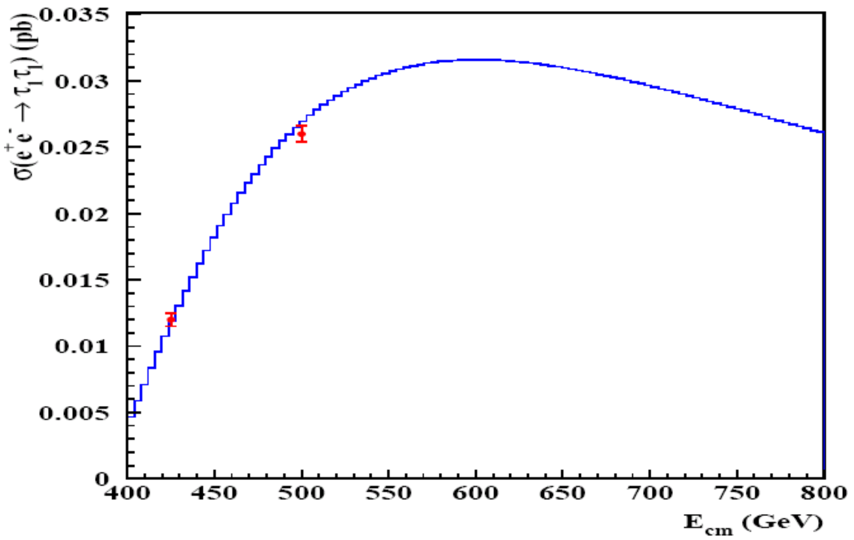
Constraining $|A_\tau|$ with $BF(H^0/A^0 \to \tau^+\tau^-)$ Measurement

A_τ scan for LCC-4 MSSM parameters with HDECAY 2.0



- $\Omega_\chi h^2$ measurement can be improved by constraining MSSM parameter A_τ
- $\tilde{\tau}/H \text{ coupling} \sim A_\tau \frac{\cos\alpha}{\sin\beta} + \mu \frac{\sin\alpha}{\cos\beta}$
- large $|A_\tau|$ large increases $BF(H \to \tilde{\tau}_1\tilde{\tau}_1)$
- Constrain rate of $H \to \tilde{\tau}_1\tilde{\tau}_1 \to \tau^+\tau^-\chi_1^0\chi_1^0$ with $HA \to bb\tau^+\tau^-$ analysis
- $\sigma(BF(H/A \to \tau^+\tau^-))$= 15% → **$|A_\tau|$ < 250 GeV**

LCC-4 Measurements



- Measure $M(\tau_1)$ from threshold scan
- 500 GeV
  - Measure $M(\tilde{\tau}_1)$-$M(\chi^0_1)$ from $\tilde{\tau}_1 \to \tau\, \chi^0_1$ kinematics
  - Estimate $\Gamma(A^0)$ from $\Gamma(A^0) = \frac{BR(h^0 \to b\bar{b})}{BR(A^0 \to b\bar{b})}\Gamma(h^0)\tan^2(\beta)$
- 1 TeV
  - Determine μ from $M(\chi_{2,3})$-$M(\chi_1)$
  - Precise measurement of $M(A^0)$, $\Gamma(A^0)$